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Long term Evolution of barrier beaches. A modelling perspective.

Treball realitzat per:
LE COZ, Ludovie

Dirigit per:

GRACIA GARCIA, Vicente

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CoMEM

LONG TERM EVOLUTION OF BARRIER BEACHES, A MODELLING PERSPECTIVE

Universitat Politécnica de Catalunya (UPC), Barcelonatech
30 August 2019

Ludovie Le Coz

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Øivind A. Arntsen, Dr.ing.
Associate professor in Marine Civil Engineering
Department of Civil and Environmental Engineering
NTNU Norway
Mob.: +4792650455 Fax: + 4773597021
Email: oivind.arntsen@ntnu.no

CoMEM URL: https://www.ntnu.edu/studies/mscomem

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This thesis was completed by:
Ludovie Le Coz

Under supervision of:
Dr. Vicente Gracia, Universitat Politècnica de Catalunya (UPC)

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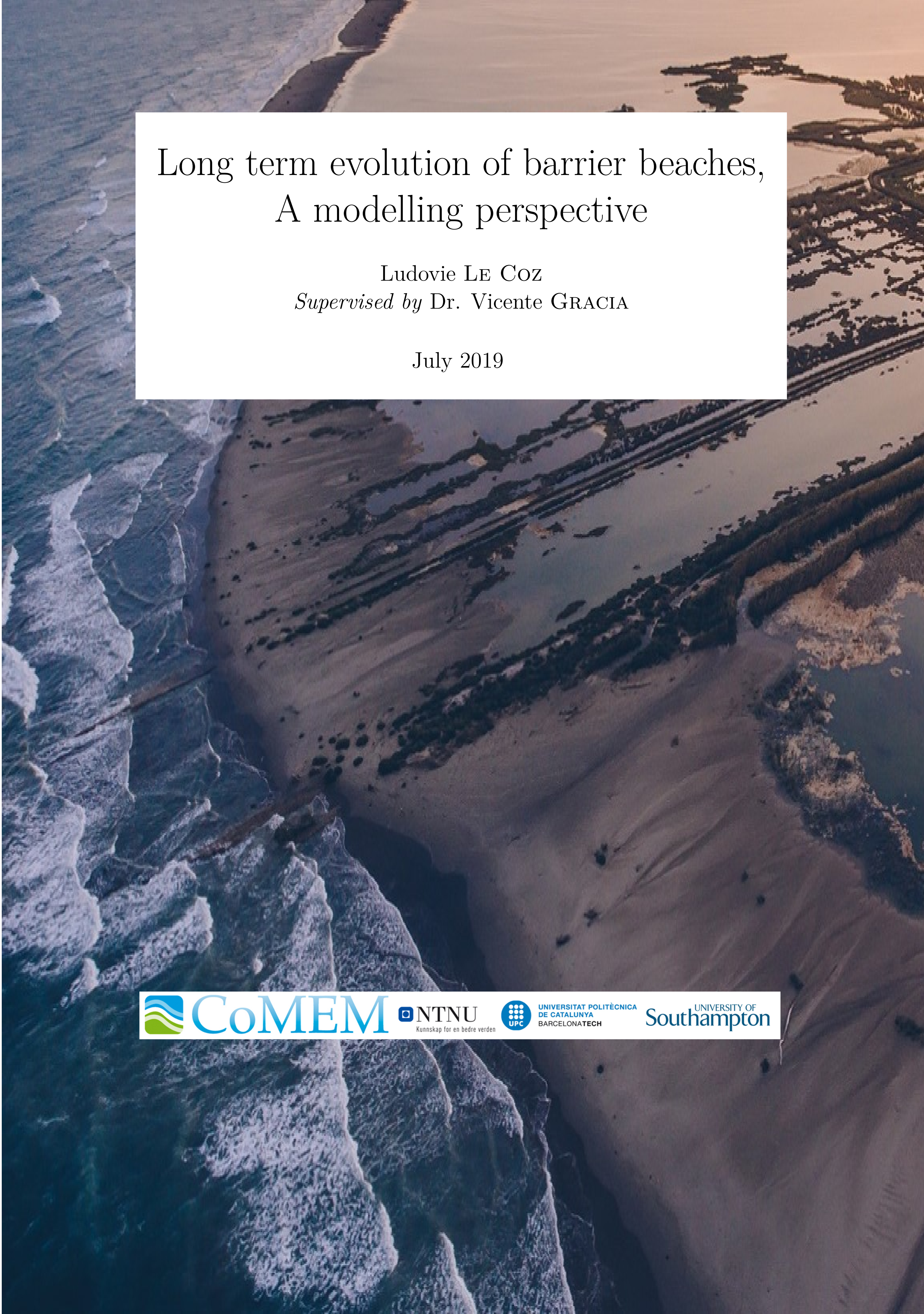

Long term evolution of barrier beaches, A modelling perspective

Ludovie Le Coz
Supervised by Dr. Vicente Gracia

July 2019

CoMEM NTNU Kunnskap for en bedre verden UPC UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH UNIVERSITY OF Southampton

Abstract

This study presents an analytical model aiming to forecast the evolution of barrier beaches around one hundred years upfront. The general goal is to create a tool for policy support that can help a proper coastal management of the particular environment formed by barrier beaches.
The model takes into account storms' impact and geotechnical settlement, trying to reproduce the complexity of forcings applied to barrier beaches. The model development is mainly based on the model developed by Rosati *et al.* (Rosati et al. 2009). Erosion and overwash are the two storms' impacts considered. The geotechnical settlement is focused on primary consolidation. The results are discussed in terms of model development, but also in terms of policy support with a tipping point approach. The model is tested with data from the Trabucador bar, at the Ebro Delta, in Spain.

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Introduction

Context

In the context of global warming and sea level rise, it is necessary to understand how the coastal environment will be impacted. Many stakes are concentrated on coastal areas, whether these are human or natural. In this study, the focus is made on a specific coastal environment, the barrier beaches, which represent 12% of the coastal forefronts. These barrier beaches are areas of biodiversity, they form unique and rich ecosystems especially when associated with deltas, which is the case for 28% of them (Pilkey and Edna Fraser 2003). They are under threat of coastal squeeze, that is to say an incapability of coastal environment to face sea level rise by retreating because of obstacles on land. A better understanding of these particular beaches could help in improving coastal management and bring some elements to scientific coastal knowledge.

Motivation and objectives

Barrier beaches are low-lying, highly sensitive coastal environments. They are subject to many processes occurring at different time and space scales as cross-shore and long-shore processes, overwash, breaching... Because of the complexity of barrier dynamics, they are usually studied through the prism of one specific process. However, global warming accelerates erosion dynamics and increases the difficulty of forecasting time evolution. Barrier evolution can no longer be understood without considering a broad picture.
Hence, there is a need to build simplified models that are including and combining various time scales and processes to wisely support decision making in barrier beach management.

The main objective of this Master thesis is to develop a numerical model that estimates the evolution of barrier beaches considering erosion, overtopping, breaching and compaction. The model will be applied at the Trabucador barrier beach at the Ebro Delta in Spain.
Designing a complex model requires first to identify the most relevant processes, then to treat each specific process in separate modules able to give (realistic) predictions, and finally to assemble the modules as a functional ensemble. The goal is to code modules for action of waves during storms, sea level rise and consolidation of compressible under-layers. The Trabucador beach is taken as the reference beach for tests and calibration of the model. In the results' interpretation, the identification of tipping points is pursued, as they present high interest for beach management (Kwadijk et al. 2010).

State of the art

Barrier beaches features and dynamics

Barrier beaches are large scale coastal sand or gravel accumulation features dominated by wave energy. They form a lagoon separating the open ocean from the mainland, as the figure 1 shows. They are protecting bays, estuaries, or mainland coasts. The main

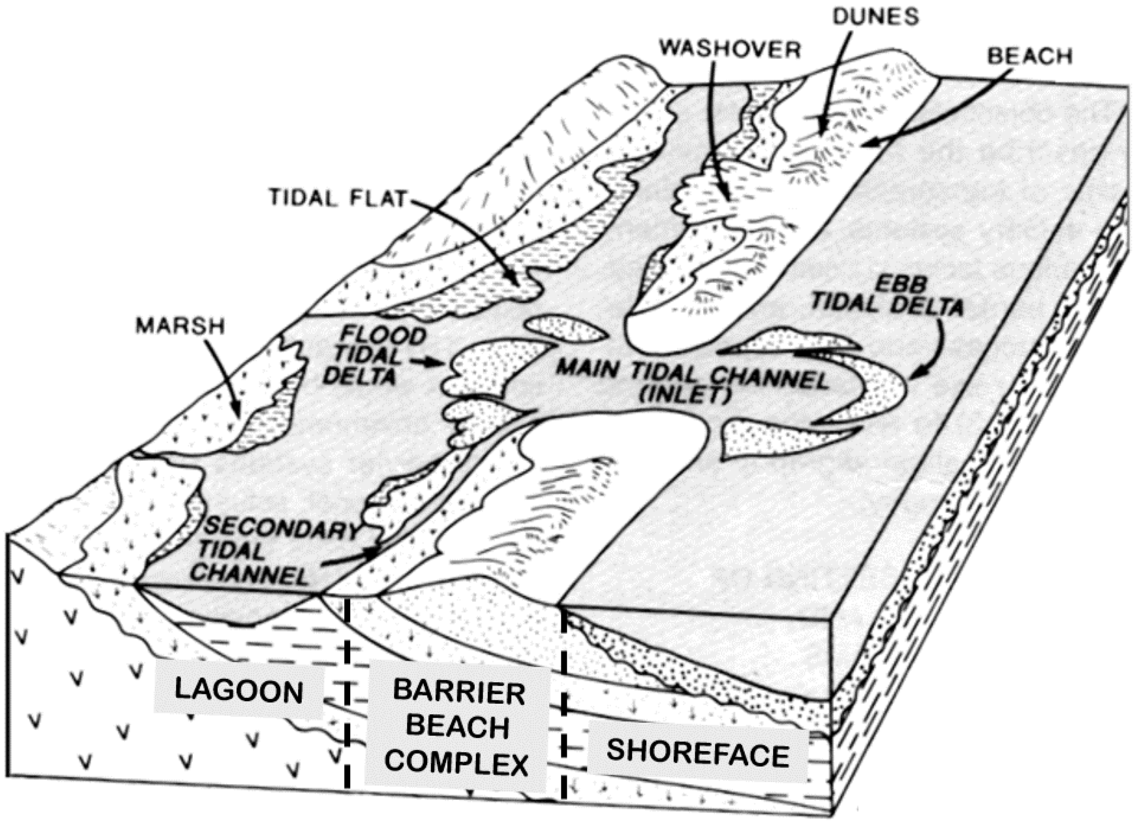

Figure 1: Sub-environments in a barrier island system, from Reinson 1992

components of interest for this study are the beach and the dunes. Tidal features are not very relevant in a Mediterranean environment.

The dynamics of barrier beaches are complex, resulting of many phenomenons. They can undergo erosion, accretion, migration, overwashing or subsidence. These mechanisms can happen at various time scales. During erosion, the shore face is retreating. Erosion can be linked with hourly processes such as storms, with seasonal and yearly processes such as variation in the regional longshore transport, or with geologic time scale (decades to century) as eustatic sea level rise, sediment consolidation or subsidence. Accretion happens when the beach is gaining sand, and thus increasing its width. It is mostly linked to seasonal, yearly and geological (eustatic decrease) time scales. Migration is the displacement of the barrier complex. It can be regressive (seaward), transgressive (landward) or lateral. It can occur at all time scales mentioned above. Overwashing mainly occurs during severe storms, it involves the displacement of sand at the back of the dune crest. It can lead to overwash fans, overwash terraces or overwash sheetwashes, depending on the intensity of the storm. Sheetwashes are causing breaching. The particular case where the whole barrier is shifted toward land by one time its width (or more) is called rollover. Theses processes are summarized in figure 2 (Doughty et al. 2006; Morton 2008; FitzGerald et al. 2008; Rosati et al. 2009).

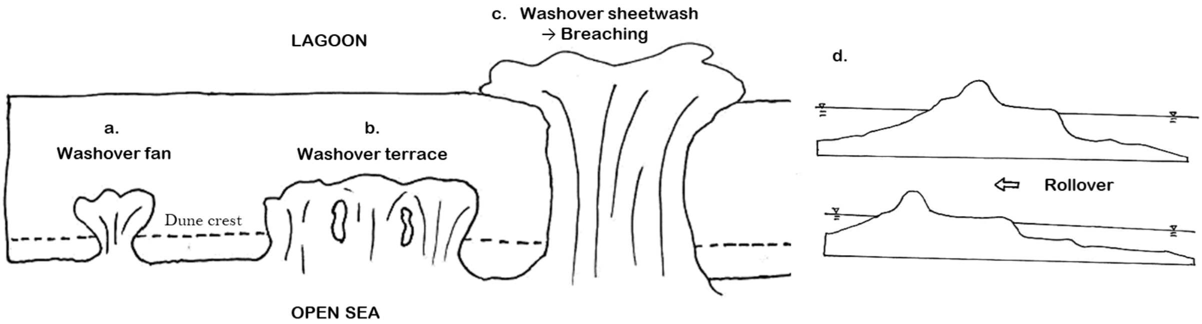

Figure 2: Overwash processes, adapted from Rosati et al. 2009 (integral version of Coastal Inlets Research Program, US Army Corps of Engineers)

Settlement of barrier beaches

Consolidation of soils is the main cause for settlement (Liu and Evett 2004). The settlement generally develops itself in three phases: the immediate settlement, the primary consolidation, and secondary compression. The immediate settlement occurs very quickly and corresponds to the ejection of air from the voids, replaced by water. It is very small in fine grained soils as clay. The primary consolidation is a long phase, in the order of years, during which the water in the voids is evacuated. This phase is the one causing the highest settlement. The secondary compression is due to plastic readjustment of grains when all the water has been expelled from the voids.

The case of Trabucador bar, at Ebro Delta

The Ebro delta is the most important delta in Spain, and hosts the only barrier beach of the Catalan coast. It shelters salt marshes and lagoons, hence it is among others a Natural Park and a UNESCO Biosphere Reserve. The delta was originally considered as a microtidal delta dominated by fluvial regime and waves, but it is now regarded as mainly dominated by waves because of the reduction of river transport due to dams (Palanques and Guillen 1998). The Trabucador bar is located at the south of the delta, as it can be seen on figure 3. It is 5 km long, between 150 and 200 m wide, its maximum heigh is 1.5 m. It ends with Banya spit, which is still growing due to the NE-SW longshore transport (Sanchez-Garcia et al. 2019). The Trabucador bears a salt production site, the Salinas de la Trinitat, and tourist activities. As many deltas, the geological basement is formed of layers of fine sand, silts and clays with traces of organic matter, mostly from Holocene (Benjumea et al. 2017).

Modelling barrier beach

Various models to predict cross shore profile response to storms exist, as Edune (Kriebel and Dean 1985), SBeach (Larson and C. N. Kraus 1989), CROSMOR (van Rijn 2009)

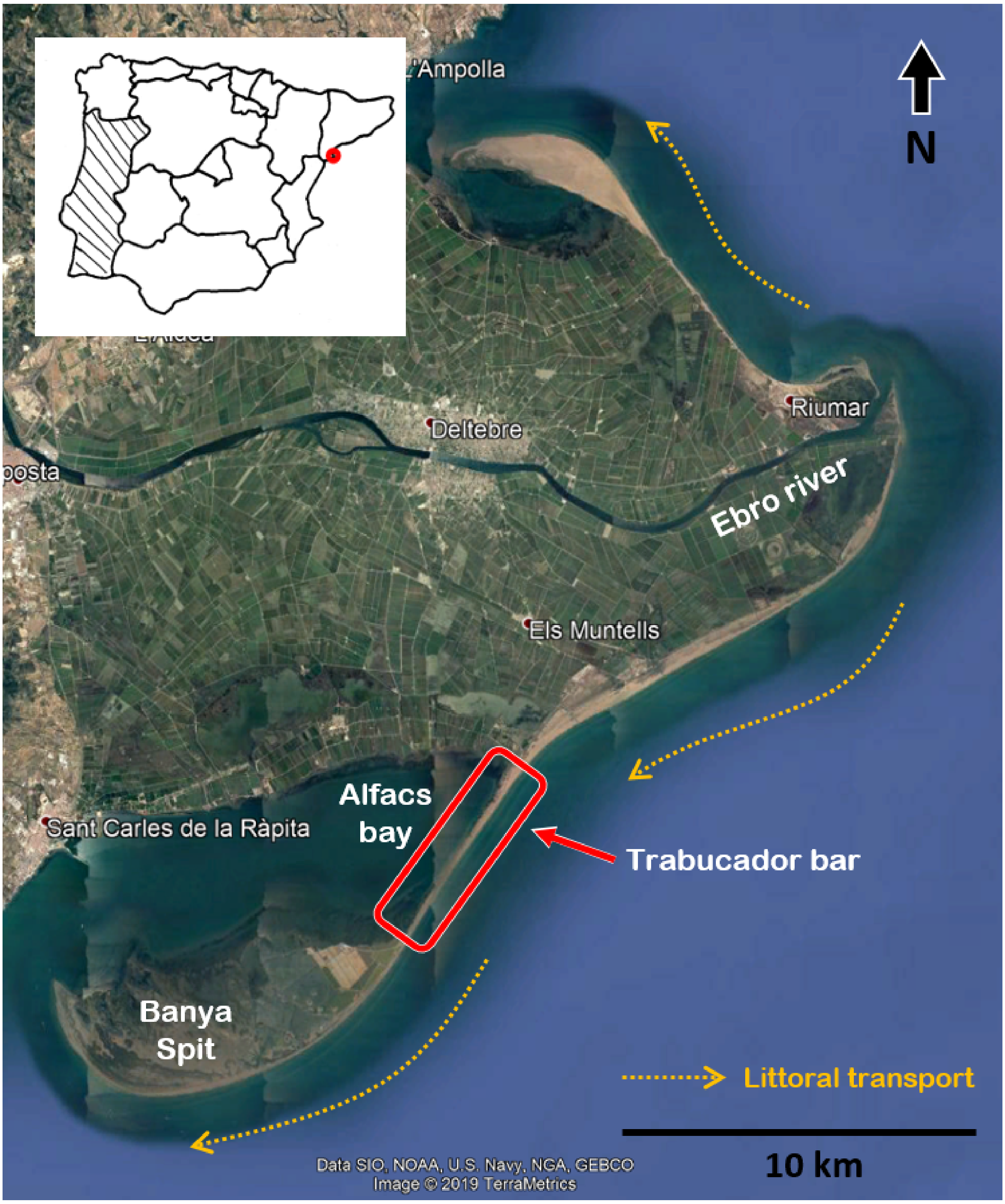

Figure 3: Trabucador bar localisation at Ebro Delta, adapted from Sanchez-Garcia et al. 2019

and XBeach (Roelvink et al. 2009). Some of them, as SBeach model, include overwash. Donnelly and Larson (*et al.*) also built up models for overwash process (Donnelly et al. 2009) (Larson, Donnelly, et al. 2009), on which the overwash model developed in this study is based. The model from Rosati *et al.* also includes settlement (Rosati et al. 2009) and is used as a general guideline. These models can be numerical or analytical.

Advantages of analytical models are the reduced time of application and the reduced quantity of data required to run them compared with numerical models. They are also less sensitive to numerical instabilities (Larson, Donnelly, et al. 2009).

Content

After the present introduction which includes the general context, motivations and aims, and a state of the art regarding barrier beaches morphodynamics and the dedicated cross-shore numerical models, methodology is exposed, results are presented, then discussed and eventually conclusions are drawn.

In the methodology section, the general set-up of the program as well as the theoretical background used to generate the modelled profile and to model the main hydraulic and geotechnical processes are explained.
The results section contains a presentation of the most relevant outcomes obtained with the model. It is subdivided into four parts, presenting the results relative to profile generation, to hydraulic processes, to long term evolution for a wave climate over 100 years and to settlement.
Then, discussion examines these results and their limits.
The conclusion sums up the main results and opens toward the future work in order to improve the model both in regard with scientific modelling and policy support.

Chapter 1

Methodology

The following part describes how the model is designed, and how to determine some of the required parameters. The Matlab code can be found in appendix L.

1.1 General concept

The main goal of the program is to select processes that have a long term impact on the barrier beach, and to estimate the morphological response on the profile. It analyses extreme storms and the geotechnical settlement in addition of sea level forecast. To sum up the general features, the program simplifies a given beach profile, generates a wave climate randomly according to specified parameters, selects the extreme events that will impact at long term the barrier morphology, and takes into account the consolidation of compressible layers. All these steps are included in the general context of sea level rise. The methodology is mostly based on the model developed by Rosati *et al.* in 2009 (Rosati et al. 2009).

For computing time's and simplicity's sake, the chosen approach is a 2D model based on geometrical considerations. The dune is simplified as a square berm and the near shore profile is assumed to be at equilibrium. The chosen section is the cross-shore one because it is supposed to be the most impacted at long term. Moreover, the goal is to determine when the dune will be submerged or completely eroded, which requires cross-shore calculations. The general structure of the program is exposed figure 1.1. The set of parameters used to run the program is adapted from the Ebro Delta data, in Spain.

1.2 Simplification of the cross-shore profile

At first, a geometrical modelling of a beach profile is generated from a cross-shore profile excel file. The excel data file contains the cross-shore distances and the associated elevation values. The user input in the program the relevant cell range of the excel file. The function `get_simplified_profile` (appendix L.3), enables to define three parts from these data: the lagoon, the dune and the offshore equilibrium profile. This function enables to extract the morphology of barrier beaches other than the Trabucador.

The lagoon is represented by a slope detected as the one between the toe of the dune and the last landward point of the profile. A visual control can be done to adjust this last

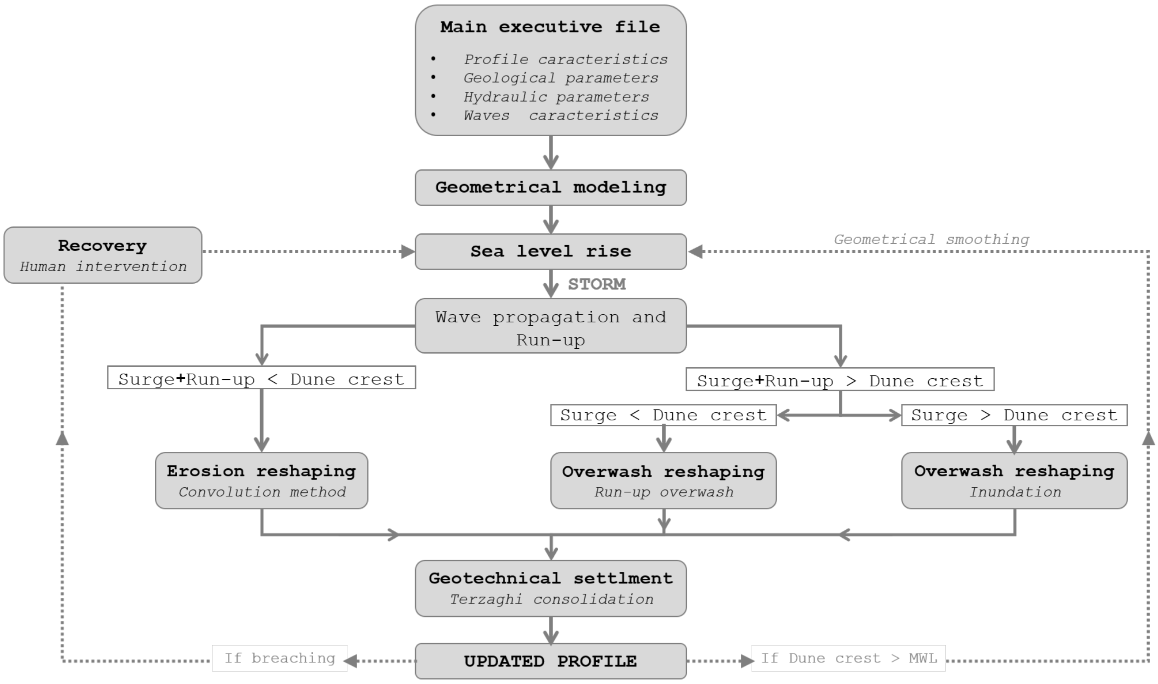

Figure 1.1: Flowchart

point so as to obtain a better fitting slope. It is to be noticed that in case the last point is higher than zero, the slope of the lagoon is set to 0.01 accordingly to some bathymetry observation of the Ebro Delta (Institut Cartografic i Geologic de Catalunya 2016-17).

The dune is set as a rectangle, as the model suggested in the convolution method (Kriebel and Dean 1993, fig 6 p.214). Both toes of the dune are defined at the zero elevation, supposedly to be the mean water level. If the mean water level is not at zero, the user can make a change of the axis system so as to fit this level at zero. The height of the dune is calculated such as the area defined by the rectangle between the toes correspond to the area of the dune between the same two points in the field data profile.

The offshore equilibrium part is defined accordingly to Bruun's equation (Bruun 1954) , later substantiated by Dean (Dean and Galvin 1976)

$$y = A\, x^{2/3} \tag{1.1}$$

with x [m] the offshore from mean water level, y [m] the water depth at x and A [$m^{1/3}$] the beach parameter driving the overall steepness. In the case of the model, the origin of the equilibrium part is not necessarily (0,0), so it has to be transposed. The equation (1.1) becomes

$$y = A\ (x + x_0)^{2/3} + y_0 \tag{1.2}$$

with (x_0, y_0) the coordinates of the origin of the equilibrium profile.

In the end, the modelled profile is composed of five segments: the lagoon slope, the dune edge lagoon-ward, the dune top, the dune edge seaward, and the parabolic equilibrium profile. Each of these segments are represented by vectors of seven rows containing the coordinates x and y of the first and last points, as well as parameters A,

x_0 and y_0 in case of a parabolic shape, or in case of a line the two coefficients of the linear equation and the flag `-inf`. Each of these segments change through time and are compiled in a three dimensions matrix. An example of simplified profile from Ebro Delta cross-shore data can be seen figure 1.2. As one can notice, the value of A parameter

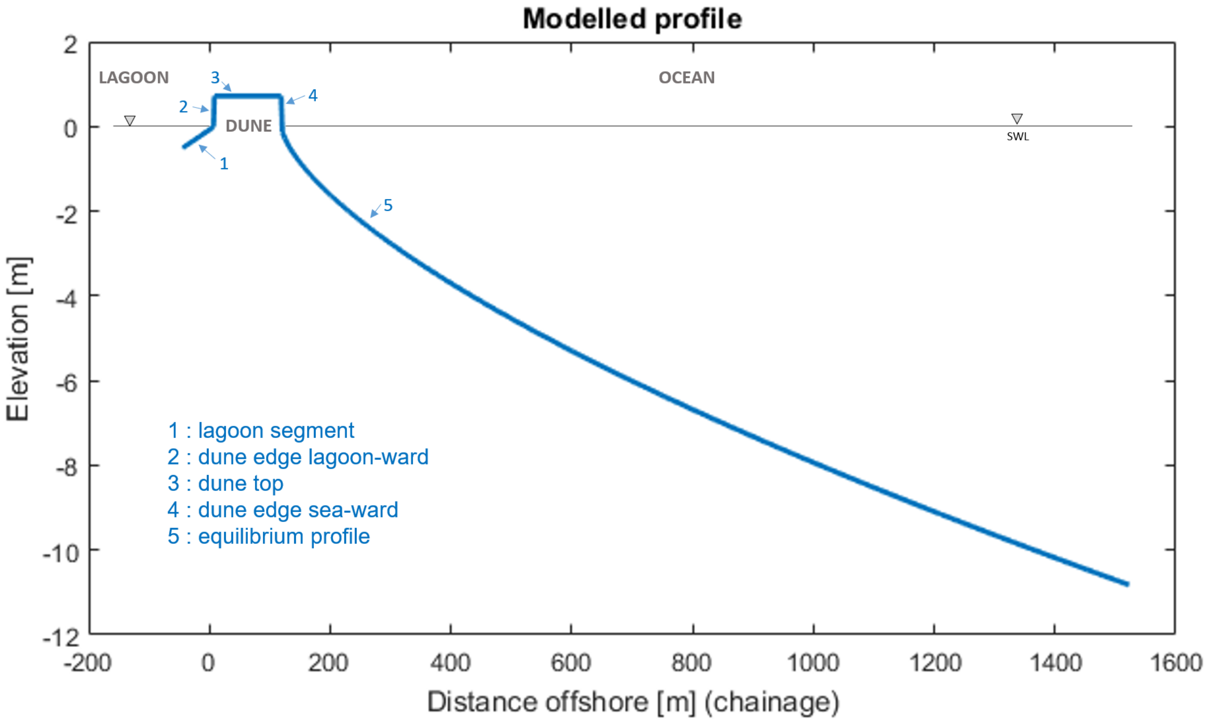

Figure 1.2: Geometrical simplification of a cross-shore profile in the Trabucador bar at the Ebro Delta, with $A = 0.086$ m$^{1/3}$

determines how the modelled profile fits the field data at the offshore part. The way it is calculated is described next section and will be discussed later.

Determination of A parameter

The A parameter is a key parameter regarding the beach morphology. It can be calculated using the function `get_A` (appendix L.7), which propose three methods plus a default one.

Method 1 is using the sediment fall velocity formula from Dean (Dean 1987)

$$A = 0.067\ \omega^{0.44} \tag{1.3}$$

with ω [**cm**/s] the particle fall velocity. See next paragraph (p. 14) for ω calculation.

Method 2 is based on the sediment grain size, as proposed by Moore (Moore 1982)

$$\begin{array}{lll} \text{if} & d_{50mm} < 0.4 & A = 0.41\ (d_{50mm})^{0.94} \\ \text{if} & 0.4 \leq d_{50mm} \leq 10 & A = 0.23\ (d_{50mm})^{0.32} \\ \text{if} & 10 \leq d_{50mm} \leq 40 & A = 0.23\ (d_{50mm})^{0.28} \\ \text{if} & d_{50mm} > 40 & A = 0.46\ (d_{50mm})^{0.11} \end{array} \tag{1.4}$$

with d_{50mm} [**mm**] the mean grain diameter.

Method 3 is based on the Coastal Engineer Manual table (Dean, Kriebel, et al. 2008) which gives a recommended value of A for a range of d_{50}. The table can be found in appendix A. The values proposed in this table are not supposed to be exact, they are rather presented as results of the statistical analysis lead by the authors.

When no method is specified, the one proposed by Kriebel and Dean is adopted which is the formula from Kriebel *et al.* (Kriebel, N. C. Kraus, et al. 1991)

$$A = 2.25 \left(\frac{\omega^2}{g}\right)^{1/3} \tag{1.5}$$

with ω [m/s] the fall velocity calculated as mentioned below. It is to be noticed that this formula is valid for $0.1 \leq d_{50mm} \leq 0.4$ and for a water temperature around 20°C (Kriebel and Dean 1993).

Fall velocity

The fall velocity is calculated in the function `fall_velocity` (appendix L.8). One option is to calculate it with the formula suggested by Cheng which presents the advantage to be valid for any Reynolds number for natural sediment particles (Cheng 1997)

$$\omega = \frac{\nu}{d_{50}} \left(\sqrt{25 + 1.2 \left[\left(\frac{\frac{\rho_s - \rho}{\rho} g}{\nu^2} \right)^{1/3} d_{50} \right]^2} - 5 \right)^{1.5} \tag{1.6}$$

with ν [m^2/s] the kinematic viscosity, d_{50} [**m**] the mean grain diameter, ρ_s and ρ [kg/m^3] the densities of particles and of fluid respectively.
An other available option is the Stokes' formula

$$\omega = \frac{g \ (d_{50})^2 \ \frac{\rho_s - \rho}{\rho}}{18 \ \nu} \tag{1.7}$$

which is valid for Reynolds numbers lower than 1 (Cheng 1997). This is the default option. It can be noticed that such a small value of Reynolds number is not very likely in coastal environment.

1.3 Hydraulic processes

Two main processes are considered : the general trend of sea level rise, and the storms. So as to estimate the impact of major storms, a wave climate is generated, using a set of parameters adapted from Ebro Delta wave boy and tide gauge data (cf. appendices C and D) (Puertos del Estado, Ministerio de Fomento 2004-17). Surges and other parameters associated to storms are generated, and the type of impact is deduced from these parameters. The nature of this impact can be erosion, run-up overwash, inundation overwash or breaching.

1.3.1 Sea level rise

The sea level rise trend is deduced from AR5 data, calibrated for the Mediterranean sea, for the 8.5 RCP scenario (Sierra et al. 2017 and IPCC AR5 WG1 2013). The equation giving a best fit to the data is such as

$$S_{LR} = 3.355^{-5}\ yr^2 - 0.1312\ yr + 128.2 \tag{1.8}$$

with S_{LR} [m] the increment of the sea level and yr [**years**] the date of the prediction (the time serie begins in 2005). The coefficient of determination (R^2) is 0.996. The year at which the sea level is set as the reference one is 2000 (*i.e.* the sea level rise is considered null in 2000).

Then, this forecast of the sea level rise is feeding the Bruun rule which gives an estimation of the morphological response (code in appendix L.19) (Bruun 1962)

$$R_{SLR} = S_{LR}\ \frac{L_*}{h_* + B} \tag{1.9}$$

with R_{SLR} [m] the retreat of the equilibrium shoreline due to the sea level rise S_{LR} [m], L_* [m] the active length between the dune and the depth of closure, h_* [m] the depth of closure and B [m] the dune height above the sea level. A sketch can be found in appendix E. Here, the depth of closure is determined from the profile data: while the standard deviation of a reduced data set is still higher than a threshold of 0.3, the data set is extended seaward.

1.3.2 Storm generation

The function `storm_generation` (appendix L.20) creates a yearly random storm wave climate from statistical data of wave buoy and tide gauge. First, the number of storms in the year is generated with a normal distribution of mean λ and of standard deviation $0.1\ \lambda$. Then, a date is attributed to each of the storms with a uniform distribution, with a minimum interval of five days between each storm (Puertos del Estado, Ministerio de Fomento 2004-17).

Next, waves parameters are generated for each storm. The wave height follows a Weibull distribution

$$H_s = A + B\ \left(-\ln\left(1 - P\right)\right)^{1/C} \tag{1.10}$$

with A [m], B [m] and C the Weibull parameters and P the probability that the wave height H_s [m] is exceeded. P is generated randomly with a uniform distribution.

The associated period is computed using the relation

$$T_p = E\ H_s^F \tag{1.11}$$

with E [s/m] and F some coefficients calibrated with the set of wave data.

The direction of the waves is picked up randomly from a frequency table built from the wave buoy measures. The statistical properties of this frequency table can be verified comparing the wave rose and the histogram, as shown in appendix D.

The surge associated to the storm is also generated from a frequency table, created from tidal gauge data of residual water level, *i.e.* when the influence of astronomical tides is subtracted. The frequency histogram of surges can be seen in appendix F. When the surge is less or equal to zero meters, the storm is deleted because the formula used to evaluate the impact of the storms gives no transport when the surge is null (see sections 1.3.4 and 1.3.5).

A sample of randomly generated storms selection can be found in appendix G.

1.3.3 Wave parameters

The parameters needed to determine which type of impact the waves have on the beach morphology are the offshore wave height and wave length, the wave period, the offshore incidence angle with the coast, and the surge when there is one. The first step is to propagate the offshore waves to the shore, then to calculate the parameters at breaking, and finally calculate the run-up.

Wave propagation

The wave propagation is computed in the function `propagation` (appendix L.10) using the linear wave theory.
The propagated wave length L [m] is calculated by iteration

$$\begin{aligned} L_0 &= \frac{g\,T_0^2}{2\pi} \\ L &= L_0\ \tanh\left(\frac{2\pi\ d}{L_0}\right) \end{aligned} \tag{1.12}$$

with L_0 [m] the wave length offshore, T_0 [s] the wave period offshore, d [m] the water depth. Then, the propagated wave height H is calculated as

$$H = H_0\ K_r\ K_{sh} \tag{1.13}$$

with H_0 [m] the offshore wave height,

the reflection coefficient $K_r = \sqrt{\dfrac{\cos\alpha_0}{\cos\alpha}}$,

the reflection shoaling $K_{sh} = \left(\sqrt{\tanh(Kd)\left(1 + \dfrac{2\,Kd}{\sinh(2\,Kd)}\right)}\right)^{-1}$,

the propagated wave angle $\sin\alpha = \dfrac{L}{L_0}\sin\alpha_0$, and wave number $K = \dfrac{2\pi}{L}$ [m^{-1}].

Wave breaking

After the propagation of the wave, the breaking conditions are calculated using the function `breaking` (appendix L.11). The breaking criterion γ is defined at 0.75 as commonly used in the linear wave theory. The goal is to seek for the depth d at which the propagated wave length H verifies $\frac{H}{d} = \gamma$. The function `breaking` starts with a couple H and d satisfying offshore conditions, and recalculate the propagated H at a reduced depth until the ratio is approaching γ close enough (at $\pm 10^{-6}$). The obtained parameters are noted H_b and d_b. From the breaking depth obtained, the cross-shore position of breaking x_b is also deduced.

Run-up calculation

The run-up is computed in the function `run_up` (appendix L.12).
To calculate the run-up, the estimation of the beach slope β is required. To do so, two options are available. Either β is set as $\frac{1}{15}$ which is the value obtained by reading the graph proposed by Wiegel with a grain size of 0.25mm, see appendix B (Wiegel 1965), or β is calculated as the average slope from breaking point to mean swash location which in the present geometric model is assumed to be the seaward toe of the dune.

In `breaking`, two methods are proposed to calculate $R_{u2\%}$ [m], the vertical elevation from sea water level exceeded by 2% of the run-ups.
Method 1 is using the empirical formula from Stockdon. Its main asset is to be applicable for all types of beaches, but it has a slight tendency to underestimate the peak run-up (Stockdon et al. 2006).

$$\begin{aligned} &\text{if} \quad \frac{L_0}{H_0}\beta < 0.3 \quad && R_{u2\%} = 0.043\sqrt{H_0 L_0} \\ &\text{else} && R_{u2\%} = 1.1\left(0.35\beta\sqrt{H_0 L_0} + \frac{\sqrt{H_0 L_0 (0.563\beta^2 + 0.004)}}{2}\right) \end{aligned} \tag{1.14}$$

with β [rad] the angle formed by the beach slope.
Method 2 is based on the formula developed by Hughes for plunging or spilling waves, and slopes range such as $\frac{1}{30} \leq \tan\beta \leq \frac{1}{5}$ (Hughes 2004). It is the one suggested by Rosati *et al.* (Rosati et al. 2009)

$$R_{u2\%} = 4.4\,(S + d_b)\,\beta^{0.7}\sqrt{A_0\left(\frac{S+d}{gT_0^2}\right)^{-A_1}} \tag{1.15}$$

with S [m] the surge, $A_0 = 0.6392\left(\frac{H_d}{S+d_b}\right)^{2.0256}$ and $A_1 = 0.14\left(\frac{H_d}{S+d_b}\right)^{-0.391}$, d_b [m] is the local water depth here set as the breaking depth, H_b [m] being the associated wave height. Hughes uses H_{m0} in the original formula which corresponds to the direct value of the wave height in the wave spectrum, here this value is taken as the propagated wave height.

1.3.4 Erosion

During a storm, if the sum of the run-up ad the surge is smaller than the height of the dune, it means that the waves are not trespassing in the lagoon, the erosion process is taking place, as shown in figure 1.3 (a.). The calculations for erosion are based on the work developed by Kriebel and Dean, the convolution method (Kriebel and Dean 1993) (code appendix L.13).

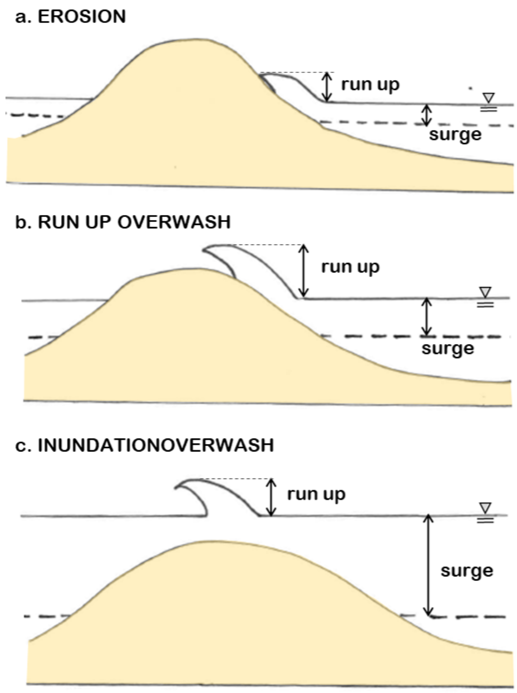

Figure 1.3: Distinguished cases of storm impacts, adapted from Rosati et al. 2009

Convolution method

The authors consider that the beach response to an erosive event presents a lag, and follows an exponential evolution of the form $R(t) = R_\infty \left(1 - \exp\left(\frac{-t}{T_s}\right)\right)$, with $R(t)$ [m] the retreat at the time t [s], R_∞ [m] the maximum potential retreat and T_s [s] the characteristic time scale of the response.

The characteristic time scale can be calculated using a formula deduced from a serie of experiments

$$T_s = C_1 \frac{H_b^{3/2}}{A^3\sqrt{g}} \left(1 + \frac{d_b}{B} + \frac{m x_b}{d_b}\right)^{-1} \tag{1.16}$$

with C_1 a dimensionless coefficient set as 320 as the results obtained by Kriebel and Dean suggest, H_b [m] d_b [m] and x_b [m] the wave height, depth and cross shore position at breaking (see the breaking paragraph p. 17), B [m] the dune height and m the linear beach slope set here at 0 since no linear part is considered in the modelled profiles.

The retreat itself is calculated in a function called `convolution` with the formula

$$R = \frac{R_\infty}{2} \left[1 - \frac{\beta_t^2}{1+\beta_t^2} \exp\left(-\frac{2\sigma t}{\beta_t}\right) - \frac{1}{1+\beta_t^2} \left(\cos 2\sigma t + \beta_t \sin 2\sigma t\right)\right] \tag{1.17}$$

with t the duration of the H_0 and T_0 conditions, $\beta_t = \frac{2\pi T_s}{T_d}$, T_s [s] the storm duration and $\sigma = \frac{\pi}{T_d}$ [s^{-1}].
R_∞ is calculated as Kriebel and Dean propose for the case of a dune with no back shore

$$R_\infty = \frac{S\, x_b}{B + D + d_b - \frac{S}{2}} \tag{1.18}$$

with S [m] the surge, B [m] the dune height and D [m] the altitude where the equilibrium profile starts set here at 0.

Profile response

Then, in the function `erosion` (appendix L.14), the morphology of the beach is updated. The dune is eroded by translating the origin of the equilibrium profile by R landward and by elevating this origin by the storm surge. Two profiles are then generated, as shown figure 1.4 (a. and b.). In the first one, the seaward limit of this new part of the equilibrium profile is determined by a volume balance between the amount of eroded sediment and the amount placed in the offshore direction. This implies that two more segments are added to the profile (compare figure 1.2 and figure 1.4 a.). Because the simplified profile contains five segments and because the accumulation of bars is not taken into account for long term response, the second profile contains no bar.

1.3.5 Overwash

Overwash occurs when the run-up plus the surge is greater than the dune height. It causes displacement of sediment in both seaward and lagoonward directions. The eroded volumes are calculated according to the formula used by Donnelly *et al.* in the overwash model they developed (Donnelly et al. 2009) in the function `overwash_volumes` (appendix L.16). Two cases are identified: when the surge is smaller than the dune and when it is greater, respectively the case of run-up overwash and the case of inundation overwash.

Run-up overwash

When the surge is smaller than the dune height, see figure 1.3 (b.), the volume overwashed is calculated as

$$q_{dr} = 2\sqrt{2g}\ K_{ru} Z_r^{3/2} \sqrt{1 - \frac{B}{R_u}} \tag{1.19}$$

with q_{dr} [m^3/s/ml] the cross-shore sediment transport rate over the dune, B [m] the dune height, R_u the run-up estimated before, K_{ru} [m^{-1}] the sediment overwash coefficient for run-up overwash and $Z_r = S + R_u - B$ [m] the height of water above the dune crest (S the storm surge [m]).

Inundation overwash

When the surge is higher than the dune height as pictured figure 1.3 (c.), the volume becomes

$$q_{di} = q_{dr} + 2\sqrt{2g}\ K_i Z_r^{3/2} \tag{1.20}$$

with q_{dr} [m^3/s/ml] the cross-shore sediment transport rate over the dune and K_i [m^{-1}] the sediment overwash coefficient for inundation overwash.

Swash zone transport during overwash

In both cases, some material is also transported seaward. The volume rate in the swash zone is calculated as proposed by Larson *et al.* (Larson, Kubota, et al. 2004)

$$q_{sw} = 2\sqrt{2g}\ K_{sw} R_u^{3/2}\ (\tan\beta_{sw} - \tan\beta_{eq}) \tag{1.21}$$

with q_{sw} [m^3/s/ml] the cross-shore erosion rate seaward, K_{sw} [m^{-1}] the sediment swash coefficient, β_{sw} [rad] the slope in the swash zone approximated here by β the beach slope and β_{eq} [rad] the equilibrium slope taken between the beginning of the equilibrium part and the depth of closure.

Profile response

All the calculated transport rates are multiplied by the storm duration [s] to obtained the total volumes displaced, called Q_{dr}, Q_{di} and Q_{sw} [m^3/ml]. The profile morphology is modified by the function `overwash` (appendix L.17). Two profiles are generated, as shown figure 1.4 (c. and d.).

The first profile response corresponds to a bar formation of Q_{dr} or Q_{di} m^3 offshore and a toe deposition of Q_{sw} m^3 in the lagoon side. The second one proposes that the dune is widened of a volume of Q_{dr} or Q_{di} m^3, and that the equilibrium profile origin is shifted but without bar formation. This second response is used in the program as the one undergoing sea level rise until the next storm.

For the first profile, in case the toe is not fitting in the lagoon side, the profile is not extended, but only the fitting part of the toe is taken into account (code appendices L.17 and L.15).

1.3.6 Breaching

During a storm, when overwash occurs and to a lesser extent when erosion occurs, it could happen that $(Q_{sw} + Q_{d*})$ is greater than the volume of the dune or that R is larger than the dune width. In such cases, it is considered that the barrier is breached. The hypothesis is made that under this circumstance, local authorities will react within three months and re-build the dune at the height it was initially, with respect of the new sea level.

1.4 Geotechnical processes

In the model from Rosati *et al.*, the primary consolidation of poorly consolidated sediment layers, such as deltaic deposits is considered (see section). This consolidation is different depending on the load that the layer had experienced before. If the soil never experienced a load as the one applied, it is under consolidated and will undergo a greater primary consolidation settlement. In the other case, it is over consolidated and the primary settlement will be smaller. The calculations are derived from Terzaghi soil mechanics theory (Terzaghi et al. 1996) (code appendix L.18).

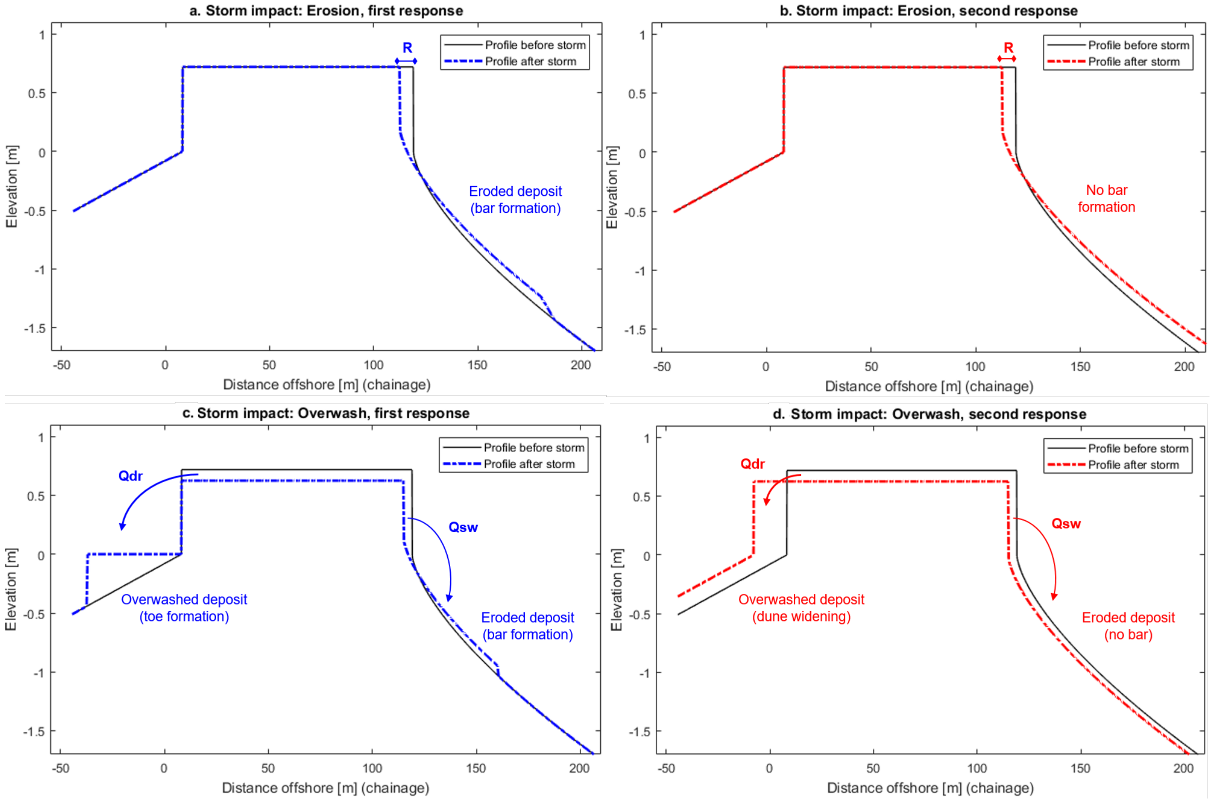

Figure 1.4: Profile response to storms. a. Erosion, bar formation b. Erosion, no bar c. Overwash, bar and toe formation d. Overwash, no bar and dune widening

Total settlement

Two formulae can be used to calculate the total settlement in a clay layer

$$Z_c = \frac{e_0 - e_f}{1 + e_0}\, h \tag{1.22}$$

and

$$Z_c = C_c \left(\frac{h}{1 + e_0}\right) \log \frac{p}{p_0} \tag{1.23}$$

with Z_c [m] the total settlement, C_c the compression index, h [m] the thickness of the compressible layer, e_0 the initial void ratio (ratio between the void volume and the solid volume) and e_f the final void ratio after consolidation, p the resent total loading on the mid-height of the layer, p_0 the present total loading minus the loading due to the present additional load.

Settlement estimation

The proportion of total settlement Z [m] reached within the time t [s] is

$$Z(t) = Z_c\ (1 - M) \tag{1.24}$$

$(1 - M)$ is the percentage of consolidation achieved at the time t, such as

$$M = 8 \sum_{n=1}^{\infty} \frac{\exp - \left(c_v t \frac{[(2n-1)\pi]^2}{4h} \right)}{\left(2n-1\right)^2 \pi^2} \tag{1.25}$$

with c_v the coefficient of consolidation [m^2/yr],t [s] the elapsed time and h [m] the thickness of the compressible layer.

The value of coefficients C_c and c_v along with p_0 depends on whether the layer is over or under consolidated. They are determined with Casagrande and oeudometric tests, as the one exposed by Rosati *et al.* presented in appendix H. These tests also permit to obtain values for e_0 and e_f. Besides, the time required to obtain a given percentage $(1 - M)$ of consolidation can also be estimated

$$t = \frac{T_v}{c_v} h^2 \tag{1.26}$$

with (T_v) the consolidation time factor that goes with a value of $(1 - M)$ such as presented in appendix I.

A simplified estimation of (T_v) can be done with

$$\begin{aligned} &\text{if} \quad (1 - M) \leq 0.526 \quad T_v = \frac{\pi}{4} (1 - M)^2 \\ &\text{if} \quad (1 - M) \geq 0.526 \quad T_v = -0.933 \log M - 0.085 \end{aligned} \tag{1.27}$$

Chapter 2

Results

This part describes some results obtained as well as the progression made to readjust some parameters. Non exhaustive examples of simulations can be found appendices L.2 and L.1.

2.1 Profile generation

2.1.1 A parameter calibration

The mean grain diameter at the Trabucador is 0.225 mm (Institut Cartografic i Geologic de Catalunya (ICGC) 2010a). The corresponding beach parameter A calculated with equations 1.5 and 1.6 is 0.0779 $m^{1/3}$. However, after checking the volume difference between the field data and the modelled equilibrium, A is adjusted to 0.086 $m^{1/3}$ (that is a sediment diameter of 0.25 mm) to ensure a best fit, especially in the part between the dune and the depth of closure, where most of the sediment displacements are taking place. Results obtained for A calibration are presented figure 2.1.

2.1.2 Simplified profile

The modelled profile obtained from a 2011 survey of Ebro Delta at the Trabucador bar is presented figure 2.2 with a beach parameter A of 0.086 $m^{1/3}$. The depth of closure obtained from field data is $h_* =$6.8 m, at a distance of 818 m.
The difference of volume between the field data profile and the modelled one in the zone including 100 m before the dune until the depth of closure is 34 m^3 (per linear meter), representing 1.2% of the in field volume of this area. The total difference of volume is 475 m^3 which represents 6% less than the total in field volume. Since most of the transport is assumed to take place in the zone mentioned above, the obtained simplified model seems acceptable, at least as a modelled sand bank. One can also note the presence of a bar, obviously not considered by the model.

2.2 Hydraulic processes

As a first approach, each code modules have been tested separately, a single storm was generated so as to run the model and keep a critical look on the obtained results (code

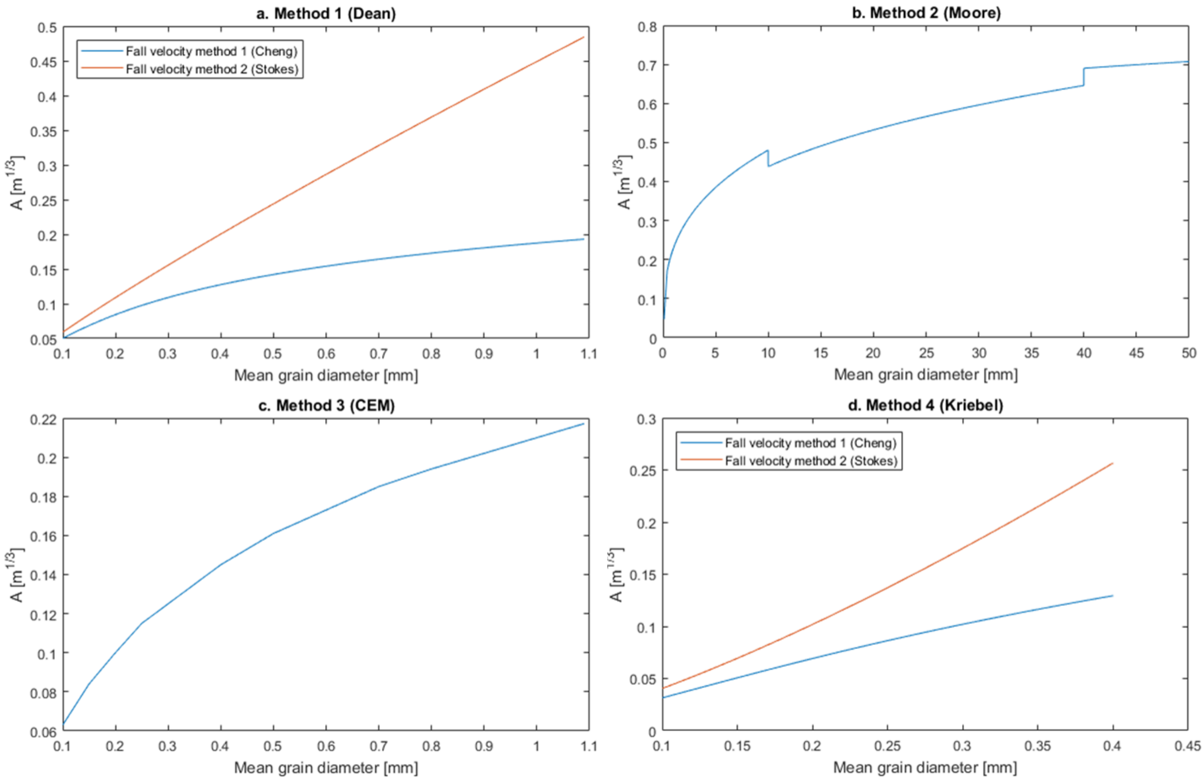

Figure 2.1: A parameter for different grain diameters, with $\rho_{sand} = 2560kg/m^3$, using the for methods presented section 1.2 (13). When the fall velocity is used, both formulae 1.6 and 1.7 are used (see 14).

appendixL.2).

2.2.1 Sea level rise

The calculated sea level rise within 100 years using RCP8.5 forecast model calibrated in the Mediterranean sea is 0.85 m (see equations 1.8). The impact of sea level rise on this profile after 100 years, without considering any other process, involve a retreat of 91 m (equation 1.9) and a rise of 0.85 m. Such profile retreat can be seen figure 2.2 (doted line). The figure 2.3 shows the forecasted values of sea level rise and retreat for the coming hundred years.

2.2.2 Storm generation

The 1st of January 2000 is taken as the initial time of the simulation, and a storm is generated randomly, in the year 2020. It is assumed in this fictitious scenario that no storms before this one has an impact on the long-term cross-shore morphology. The obtained storm characteristics are summed up in table 2.1.

During the first attempt, the dune height remained as the one obtained from the simplification of the field data, that is 0.72 m. In the 117th day of 2020, the estimated sea level rise is 0.075m (following scenario RCP8.8 in IPCC AR5 WG1 2013). The Bruun rule is then applied to the profile, causing a shift of 8.06 m and a rise of 0.72 m. After

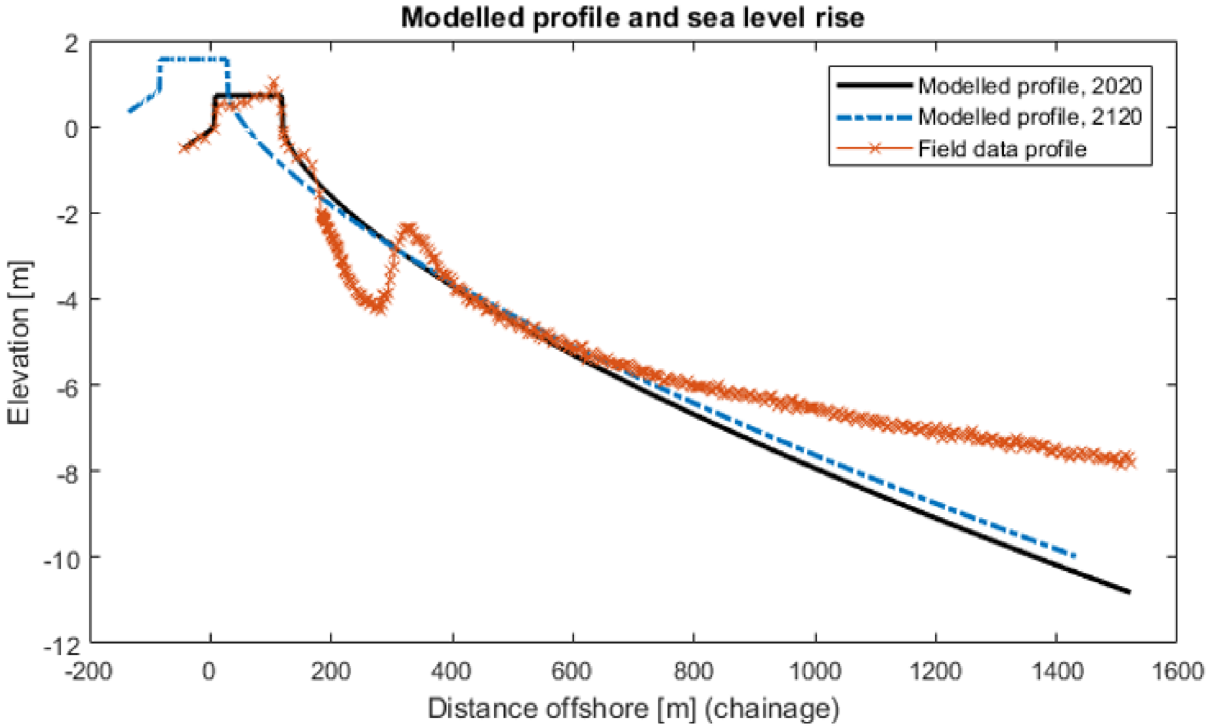

Figure 2.2: Modelled profile obtained from Trabucador cross-shore profile, and the associated sea level rise profile within 100 years

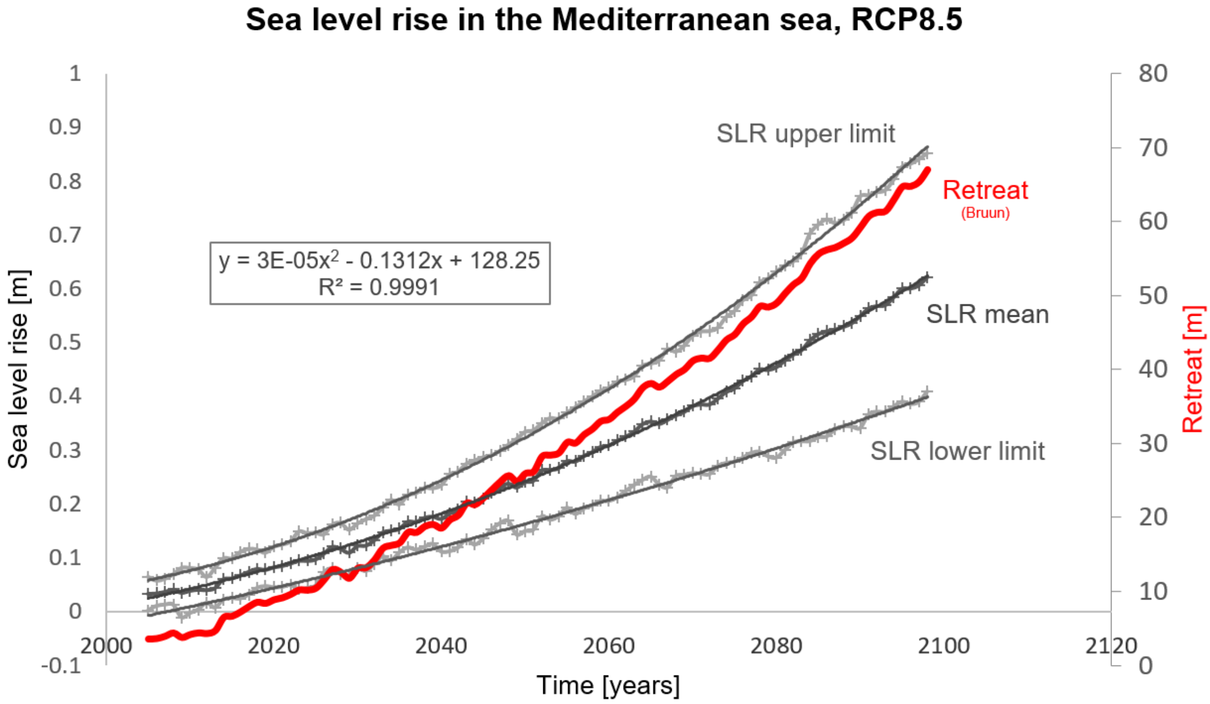

Figure 2.3: Forecast for sea level rise and profile retreat for RCP8.5 scenario

propagation, the breaking characteristics of the waves are H_b =3.99 m, d_b =-5.11 m and x_b =576.9 m (see section 1.3.3). The calculated run-up 2% (from equation 1.14 with a

Year [yrs]	2020
Day of the year [day]	117
H_s [m]	3.92
T_p [s]	7.93
α [deg]	90
S [m]	0.13
Storm duration [hrs]	24

Table 2.1: Parameters of the first storm of 2020

slope angle taken as suggested by Dean, Kriebel, et al. 2008) is 1.38 m.

2.2.3 Erosion calibration

Knowing that the surge plus the run-up is equal to 1.5 m, the dune height can be increased so as to check the erosion process. In a second attempt, the dune height is set as 2 m. Under these conditions, the barrier is not breached, and the resulting erosion can be seen figure 2.5 (b.). The obtained retreat from equation 1.17 is 1.13 m, and the corresponding eroded volume is 2.2 m^3, which appears small and is not fitting very well the volumes obtained in case of overwash.

The small value of the surge can explain this result, considering the equations 1.17 and 1.18. When the surge is set to 0.4 m, the obtained retreat is 3.56 m and the eroded volume 6.13 m^3, which is still smaller than expected.

It could also be that the characteristic time scale T_s is not well calibrated. From the equation 1.16, the obtained value is 35 5585 s ($\approx$99 h). Yet, in equation 1.16, the coefficient C_1 is taken equal to 320 following Kriebel and Dean recommendations (Kriebel and Dean 1993), which might not adapt well to the case studied here. A parameter study of C_1 can be found in figure 2.4. Taking a C_1 value of 30 and keeping the 0.13 m surge, the corresponding retreat is 4.15 m, representing an eroded volume of 8.3 m^3. The sudden drop of the volume is in all likelihood due to the accuracy of the method used to calculate volumes.

2.2.4 Overwash calibration

In these conditions, the surge plus the run-up is 1.5 m so the dune is overwashed, and the surge is 0.13 m so the beach is not inundated, it is a case of run-up overwash. The obtained rate are q_{dr} =0.0628 m^3/s and q_{sw} =0.0013 m^3/s, so in the total duration of the storm Q_{dr} =5425 m^3 and Q_{sw} =114 m^3. Such volumes are huge and not realistic, even compared with extreme historical breaching storms as for example the one that hit Trabucador bar on October 1990 (Sanchez-Arcilla and Jimenez 1994). For this storm, the transported sediment was roughly 70000 m^3 in 89 hours, impacting a zone of 2000 m length, so the rate was in the order of magnitude of 0.0001 m^3/s/lm. Being given that the volume of the dune is 80 m^3, such storm entirely overwashes the dune and causes a breach, as it can be seen on figure 2.5 (a.).

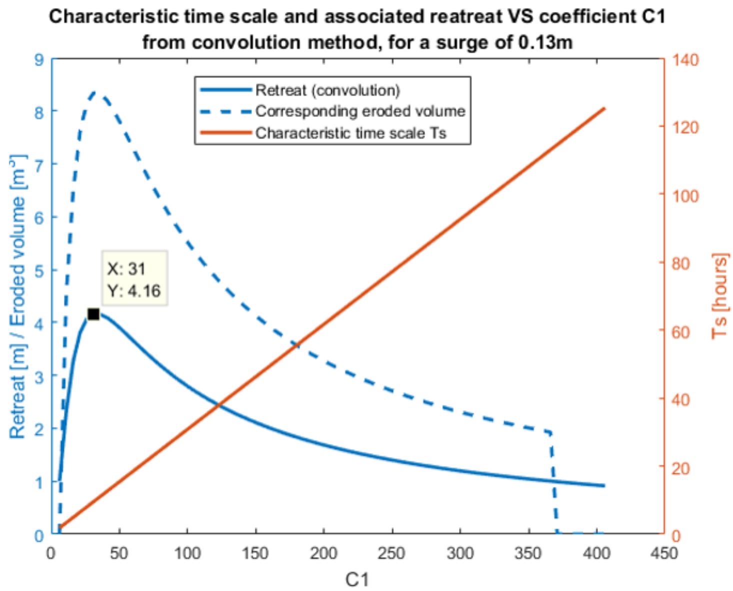

Figure 2.4: Calibration of C_1 parameter for a storm surge of 1.3 m

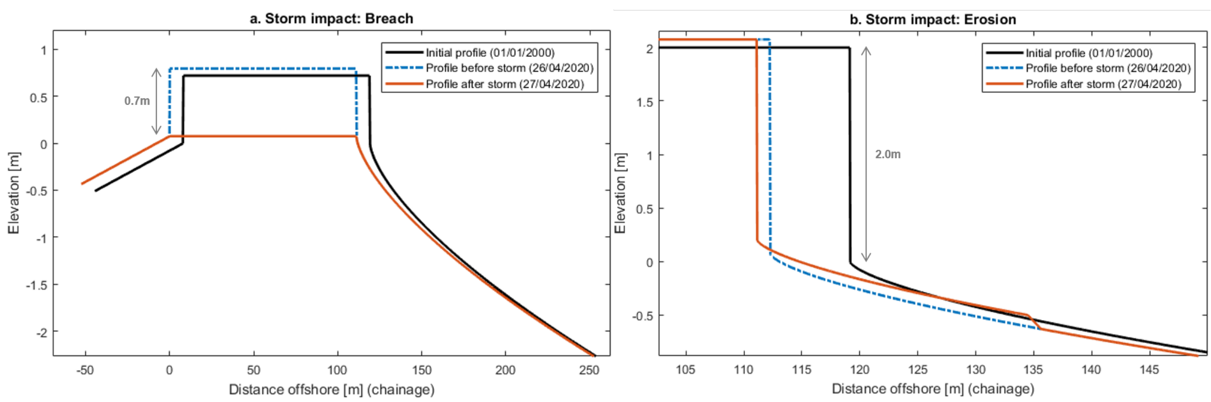

Figure 2.5: Breaching of the barrier due to the storm presented table 2.1

Key factors that influence the transport rate are K_{ru}, K_i and K_{sw} (equations 1.19, 1.20 and 1.21). In the first attempt, K_{ru} and K_i are set at 0.005, and K_{sw} at 0.0016 according to Rosati *et al.* model calibration (Rosati et al. 2009). However, these values were defined for studies in the Atlantic ocean. A study by Larson *et al.* aiming to apply an analytical model for overwash, has been realized in the Ebro Delta, at the Trabucador bar (Larson, Donnelly, et al. 2009). In this study, K_{ru} and K_i have representative values between 0.0001 - 0.0007. From different attempts and comparison with the storm of October 1990, the values for K_{ru} and K_i are set as 0.0001. For the K_{sw} coefficient, the source article highlights the importance of this parameter, and suggests values between 0.001 - 0.0045 (Larson, Kubota, et al. 2004). Because of the lack of calibration examples on the Mediterranean coast, the K_{sw} value is kept at 0.0016.

The new obtained volumes for the storm presented table 2.1 are q_{dr} =0.0013 m^3/s and q_{sw} =0.00019 m^3/s (Q_{dr} =109 m^3 and Q_{sw} =10 m^3), which seems more in accordance with the reality, even though q_{dr} is still higher than expected. The obtained profile after breaching is presented figure 2.5 (a.).

2.3 Long term evolution of the retreat

A random generation of storms for a 100 years period (code appendix L.1) gives 340 events, among which the highest wave height is 6.8 m with a period of 10.8 s and a surge of 0.291 m in June 2112. The highest surge is 0.299 m, and is obtained for another date, in April 2099. See paragraph 1.3.2 and 2.2.2 for more details on storm generation. The evolution of the retreat combining sea level rise and storms within 100 years is presented figure 2.6, using RCP8.5 scenario as mentioned in section 2.2.1. The mean retreat caused by storms is 3.9 m, the maximum retreat due to a storm is 9.7 m. In this simulation, breaching occurs 23 times in 100 years, which represents 6.5% among the selected 340 extreme events. The storm with the highest wave height led to a breach, unlike the storm with the highest surge. The table containing the parameters of the breaching storms can be found in appendix J, and the table for all the storms in appendix K . It has to be

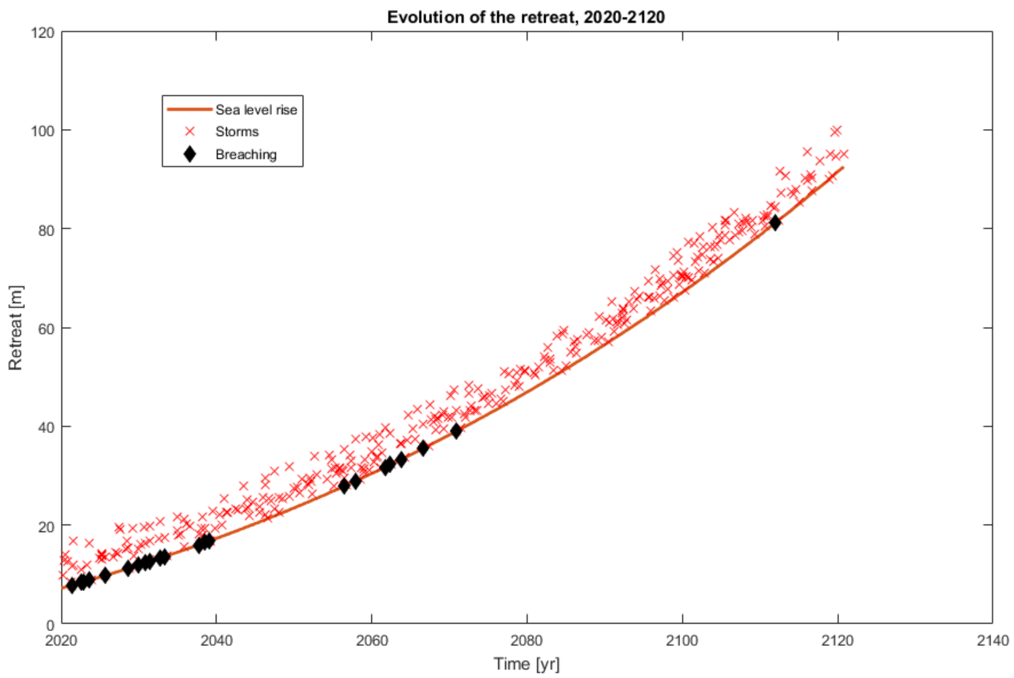

Figure 2.6: Evolution of the retreat in 100 years combining sea level rise and storms

understood that both processes of storms and sea level rise lead to retreat, however not in the same way. On the one hand, sea level rise causes a retreat by shifting the whole profile. On the other hand, storms are cauding a retreat by eroding the barrier, so in this case the width of the dune is reduced and the location of the barrier remains.

2.4 Settlement

In a geological survey of the Ebro Delta lead by the Cartography and Geology Institute of Catalunya (ICGC), some characteristics of a compressible clay layer (referenced as Q_{Hprd}) are studied (Benjumea et al. 2017). In particular, it is mentioned that this layer is underlying 45 m beneath the Trabucador bar. Its thickness varies between 25 and 43 m from the east side of the Trabucador bar to the west side. After examination of the thickness map, a thickness of 35 m has been chosen to carry out the calculations. Some geotechnical test where carried out on borehole samples (in the appendix 1 of Benjumea et al. 2017), relevant results are copied in table 2.2. Figure 2.4 shows the evolution

e_0	0.954
e_f	0.55
C_c	0.28
P_0 [kg/m^2]	4500
c_v [m^2/s]	$6.5 \cdot 10^{-8}$

Table 2.2: Oedometer tests results for clay/sand unit (from Benjumea et al. 2017 appendix1 table A5)

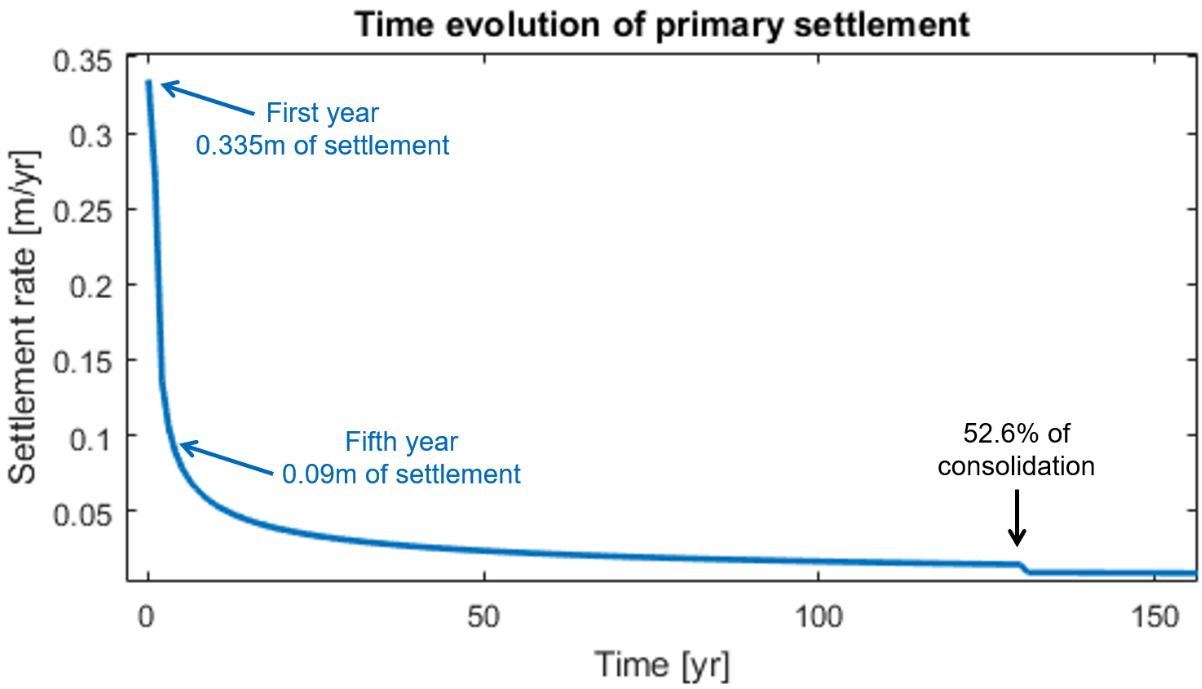

Figure 2.7: Evolution of the settlement rate of the clay layer due to primary consolidation

of settlement rate due to primary consolidation (code appendix L.2). For the figure, a maximum settlement of 8m was calculated using equation 1.22, which corresponds to the hypothetical case of a very heavy load that would cause all the water to leave the pores, as done during the oedometric test. This rate is high the first years, of tenth of centimetres, diminishes quickly within 6 years and then tends to a value lower than a millimetre per year. The step that can be seen around 135 years is due to the calculation of the consolidation percentage using formula 1.27. This results gives an order of magnitude of the primary settlement phenomenon, however, it is difficult to estimate the present percentage of consolidation in the layer, and thus to find the associated year so as to estimate which settlement rate to expect. Being given the estimated subsidence though, one can expect that the primary settlement is contributing to no more that a few millimetres per year to the total settlement.

Some calculations can be done to get an idea of the impact of the dune migration (over a distance greater or equal to its own width) over non consolidated clay, using equation 1.23. First, the estimated load due to the dune is $1.166 \cdot 10^9$ kg, taking a width of 110 m, a height of 1 m and a length of 4000 m, and a self weight of 2650 kg/m^3. Then, the vertical stress at the depth of the compressible layer is calculated using the approximate method (Liu and Evett 2004)

$$p = \frac{P}{(B+z)(L+z)}$$

with p the approximate vertical stress [kg] at the depth z [m], P [kg] the total load at the surface, B [m] the width of the loaded area and L [m] the length of the loaded area. The obtained vertical stress at the mid-height of the compressible layer is $\frac{1.166 \cdot 10^9}{(110+62.5)(4000+62.5)} = 1.664 \cdot 10^3$ kg/m^2. Injecting this in equation 1.23 gives a maximum settlement of 1.5 8m. This result has to be understood as the highest value of settlement that can be expected in case of a barrier migration, and is unlikely to happen.
Calculations also have been carried out for a barrier length of 800 m, corresponding to the widest breach ever observed so far (during the October 1990 storm, see Sanchez-Arcilla and Jimenez 1994), and gives a maximum settlement of 1.49 m.

Chapter 3

Discussion

In this part, the relevance and accuracy of results are discussed. A criticism of the model is sketched.

3.1 Profile modelling

This model is based on analytical concepts applied to the equilibrium beach profile theory. This theory developed by Bruun (Bruun 1954) is widely used in coastal sciences, however it implies strong simplifications. Among these simplifications, the most obvious is the smoothing of the bathymetry. Thus in this model, the impact that could have sand bars on the evolution of the morphology is ignored.

As mentioned in section 1.2, the modelled dune's height is the one obtained by volume conservation of the field data dune profile into a rectangular shape. Doing so, the dune height is under estimated as it can be seen figure 2.2 (here the modelled dune is 30 cm lower than the highest dune point of field measures).

One can also discuss the chosen value of A parameter, explained in section 1.2, considering the range of values obtained with the different methods (see figure 2.1). Especially since the results seem very sensitive to A value, as the figure 3.1 shows. This figure was obtained with a dune set at 1.5 m and the storm is the first storm of the simulation (see appendix K, 1st line). This figure also highlights a tipping point: the highest value of the retreat is obtained for a A of 0.06 $m^{1/3}$. It appears that the choice of A parameter is a critical point when calibrating the model, whereas this parameter is very difficult to adjust (also see sections 1.2 and 2.1.1).

3.2 Hydraulic processes

3.2.1 Sea level rise

As figure 2.3 shows, the best fitting function for sea level rise is a polynomial and not an exponential as it is usually done, however the behaviour is still close to an exponential one.

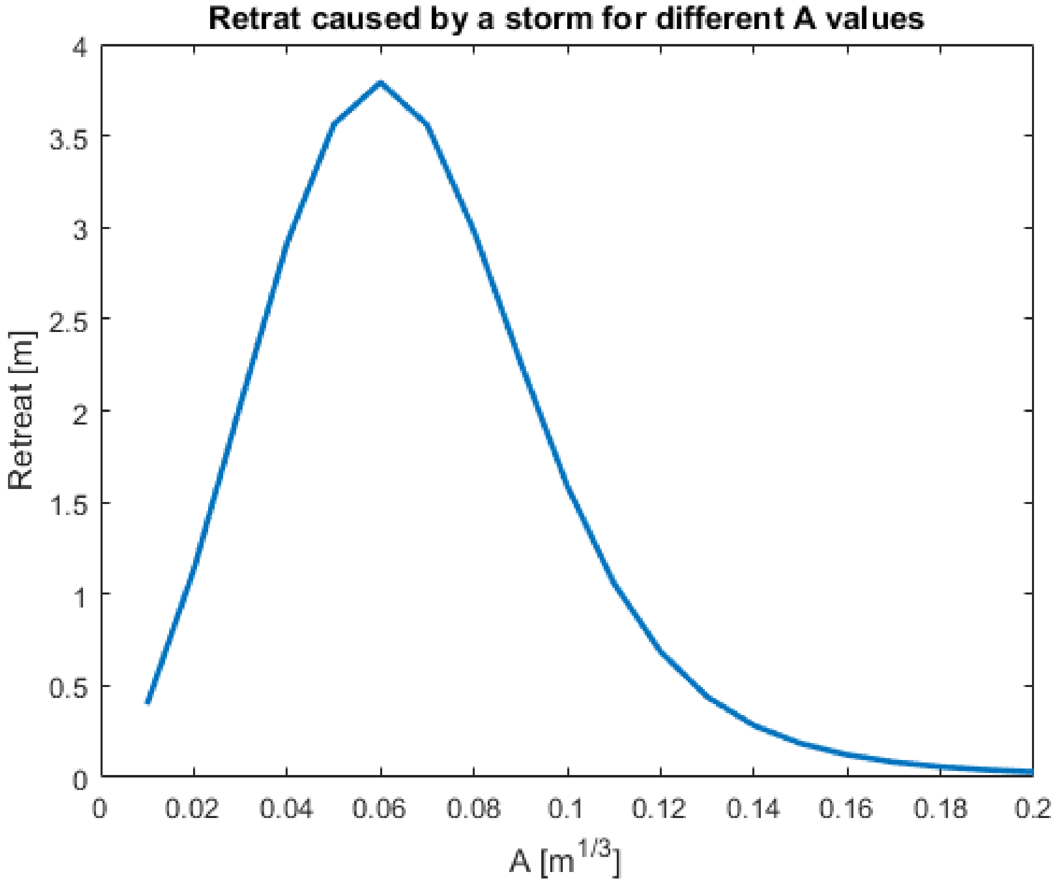

Figure 3.1: Retreat obtained for a given profile and a given storm

The sea level rise impact proposed by Bruun is also challengeable even though it is still widely used (see for example Cooper and Pilkey 2004 and Aagaard and Sørensen 2012). One reason for which it is criticized is the hypothesis that the longshore transport is not having impact on the long term perspective, as discussed section 3.2.2.

It could be intended to code an alternative to the Bruun rule, using instead the "bathtub effect". This simply means that instead of retreating, the barrier beach is staying at the same location while that the mean water level is rising. This can be understood as a lowering of the dune height, and would probably lead to a quick loss of the barrier.

3.2.2 Storm approach

Overwash considerations

For the obtained results, 23 cases of overwash occurred, which correspond to the 23 cases of breaching. Even though it is theoretically possible that overwash occurs without breaching (as it has been computed with test values of Q_{dr}, Q_{di} and Q_{sw}), this situation is not happening.

Regarding the calculation of Q_{dr} or Q_{di} and Q_{sw}, the associated retreat is different depending on the first volume taken. If Q_{d*} is taken out first, the retreat will be bigger than in the case of Q_{sw} taken out first, as figure 3.2 illustrates.

Moreover, the coefficients K_{ru}, K_i and K_{sw} are set with poor confidence since the cal-

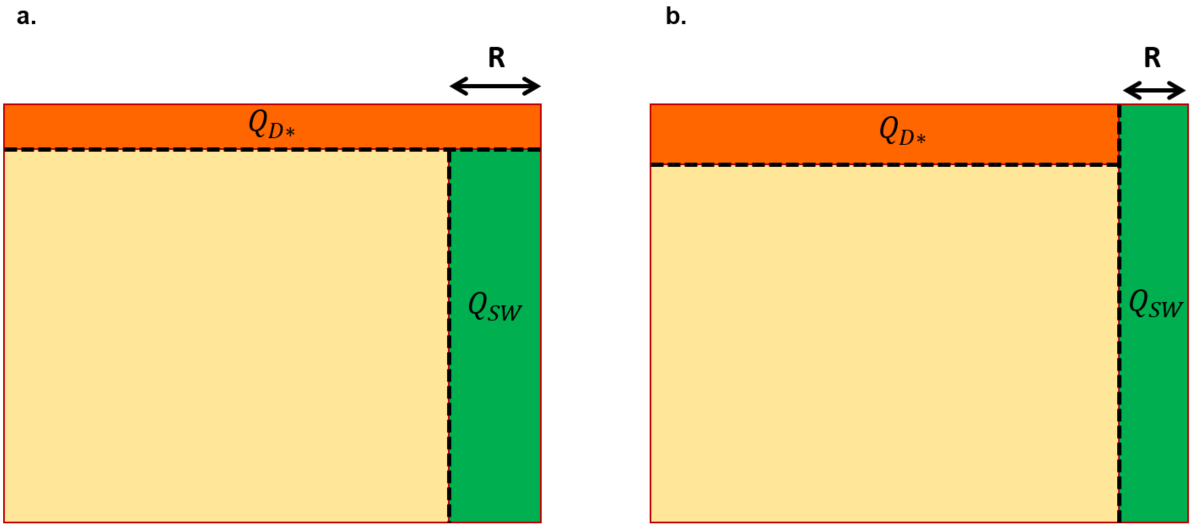

Figure 3.2: Retreat obtained for different ways of taking out Q_{d*} and Q_{sw}, a. Q_{d*} first, b. Q_{sw} first

ibrations proposed by Donnelly *et al.* are done for beaches of the Pacific that are not matching this case of study (Donnelly et al. 2009).

In case of overwashing causing a breach, the sand distribution on the other side of the barrier is not taken in account. If the sand is deposited in a way that broaden the dune, breaching would no necessarily occur even if $(Q_{d*} + Q_{sw})$ is larger than the dune volume.

Storm generation

The main bias for storm generation are that the storm duration is set at 24 h and that wave height and period is supposed to be constant during the whole duration. Actually, the duration could also be generated with an adjusted random function, for example a bell function with a peak would reproduce more accurately the wave height behaviour though time. This second assumption is thus overestimating the impact of a storm. Furthermore, only storms with a surge are selected in the model, according to the convolution method formula (see section 1.3.4). However, it is very likely that a storm with very high waves has an impact in the long run.

One can suggests that for more accuracy, the frequency of storms per year could be increased toward the end of the simulation period, as more extreme events are expected in connection with climate change (Francis and Vavrus 2012).

Post-storm recovery

The model does not take into account the post storm recovery that has been observed in some natural dune systems, even for extreme events. Estimating recovery volumes and speed requires a detailed study of the area (Bullard et al. 2019). For simplicity's sake, the longshore sediment transport is ignored. However, this transport can help the recovery. In the Ebro Delta, the net longshore transport is estimated around 471 000 m^3/yr (Institut Cartografic i Geologic de Catalunya (ICGC) 2010b), which could potentially fix breaches. Also, the wind sand transport can be an important factor for dune systems, and is not included in the model. To give an order of magnitude, CEDEX estimated the wind transport in the south part of Ebro delta at more than 48 000 kg/m/yr (CEDEX 1996).

Moreover, in the case of the Trabucador bar, the delta dynamic is not taken into account even though it plays a major role in the delta morphology. The sediment supply carried by the river is reduced by the dams that enhance erosion at the wave attacked areas (Palanques and Guillen 1998). In the case of the presented model, this wave dominated tendency of the delta dynamic is matching the storm impact approach.

3.2.3 Long term evolution

The results presented in section 2.3 (especially see figure 2.6) show that breaching can occur very early in the simulation. It is not a surprising outcome since such breaching event already took place at the Trabucador bar. It shows that the bar is threatened by upcoming storms and it will obviously still be the case in the future for about 6% of the storms.
Besides, the non homogeneous time repartition of breaching events can be noticed. The breaching events seem gathered in groups, and mainly occurring at the beginning of the simulation. This distribution is only a coincidence due to the random generation of waves.

A tipping point regarding storm impact at long term could be found by analysing the characteristics of the minimal storm causing breaching, and thus with the statistical wave data, the likely time delay for that storm to happen could be found. This means solving the equation $(Q_{dr} + Q_{di} + Q_{sw}) \geq Vol_{dune}$. However resolving this equation is not straightforward because overwash fromulae are not directly including the wave parameters. Hence, a statistical approach based on many simulation might be appropriate.

The main challenge that faces the modelling at long term is the integration of different time scales. Indeed, the erosion due to storm is a matter of hours, maximum a few days, and it is uneasy to predict whether such an erosive event will have an impact on the morphological evolution years later. The model also try to add the effect of sea level rise and settlement which occur at the scale of 50 years. The very large time scale phenomenons as the geological movements of Earth are not treated.

Another factor that can change the evolution of the dune is the anthropic activity. It happens that so far, the dune had been rebuilt or nourished several times (Sanchez-Garcia et al. 2019).

3.3 Settlement

The obtained results are in the range of the dune height. Yet, they correspond to very high values of settlement that can be regarded as the maximum ones to expect. When the breach is less wide, the settlement phenomenon will obviously be more limited in space, even though some lateral diffusion occurs when the vertical load is transmitted in depth.

The evolution of the settlement rate shows that the main settlement will occur in the few years following the barrier migration, however, it is very hard to predict the soil behaviour when important volumes of sand are rapidly moved by close storms. The difficulty to estimate settlement impact lies in knowing how much the newly loaded soil is already consolidated.

The values obtained have a limited reliability because of the approximations done during calculations, the precision of the formula, and the lack of geotechnical test results sources. Indeed, in the survey from the ICGC (Benjumea et al. 2017), the analysed samples are from a borehole in the middle of the delta plain, at several kilometres from the Trabucador bar (borehole S2), and no Casagrande consolidation curve was build. Moreover, the geological study shows that the thickness of the considered layer is not consistent along the bar, and this was not taken into account in the calculations. Besides, some other intermediate clay levels might also interfer with the load diffusion, thus with the settlement.

Nevertheless, the settlement rate evolution curve (figure 2.7) leads to distinguish two phases in the primary consolidation, with a potential tipping point around five years. Before this point, a quick settlement is to be expected, and some measures such as dune raise might need to be considered to avoid a dune sinkage. It also seems, in accordance with the subsidence data from the ICGC study around 2-3 mm/yr, that the present state of primary consolidation has reached the second phase. Subsidence might be partly explained by the secondary consolidation process.

3.4 Management perspective

As mentioned before (section 1.3.6), it is assumed that the dune will be rebuild in case of breaching. If knowing which type of storm will cause breaching, it becomes possible to coordinate with storms forecast and plan intervention measures. For example, if several breaching storms are forecast in a short time period, it could be decided to rebuild the dune only after the storm series.

Whereas according to the Bruun rule the barrier profile can adapt by migrating landward, provided that backshore conditions allow it, the profile cannot accommodate settlement. Thus settlement may play a key role in the long term evolution of the profile.
Because of this possibility, it seems relevant to realize geotechnical campaigns so as to estimate how much consolidation the soil has already experienced and then forecast with more accuracy the behaviour of the barrier.

Because the profile is expected to migrate during sea level rise, if the decision is made to keep in place the barrier at the location it has, the profile would not be able to accommodate sea level rise and the barrier would be likely to disappear quickly. A poor management of the barrier backside preventing the barrier migration could also lead to the same effect.

Conclusion

This study developed a model of barrier beach response at long term to storms and geotechnical forcings. Without surprise, the model confirms that the Trabucador bar is already under threat of extreme events.
The model predicts a retreat of about 100 m and a rise of about 1 m due to sea level rise within a century. The mean retreat to be expected form a storm is about 4 m. The role of settlement in the long term evolution of the barrier beach is difficult to estimate, it might be neglectable with respect to storm impact, however it could lead to a decrease of about 1.5 m in 100 years, with a fast evolution in the first five years. The model also shows a quite high sensitivity to variations of A parameter, reminding the necessity of proper calibration in order to obtain relevant results.

In order to go further, several tracks can be explored.
A complete sensitivity test could be carried out and an accurate calibration with better data set, especially for geotechnical settlement, could lead to more reliable results. The code might be optimized, especially in the way the geometry is treated. It could be interesting for management to try to define a "tipping storm(s)", that is the storm parameters combinations that cause breaching for a given profile. Testing the model in other barrier beach systems than the Ebro Delta could be a way to improve it.
More processes could be added, such as the wind transport. A more accurate morphology of the profile could be obtained with finite differences method. However, the aim of this model is to combine several processes, although still simple enough to give results rapidly and easily.
A user interface could be programmed, attached with an user guide so as to facilitate the learning and use of the model. Some advices relative to barrier beach management, and communication campaign could help in giving to the decisions makers a better understanding of the situation and a better overview of the available solutions.

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Appendices

A Recommended A values from CEM (Dean, Kriebel, et al. 2008)

EM 1110-2-1100 (Part III)
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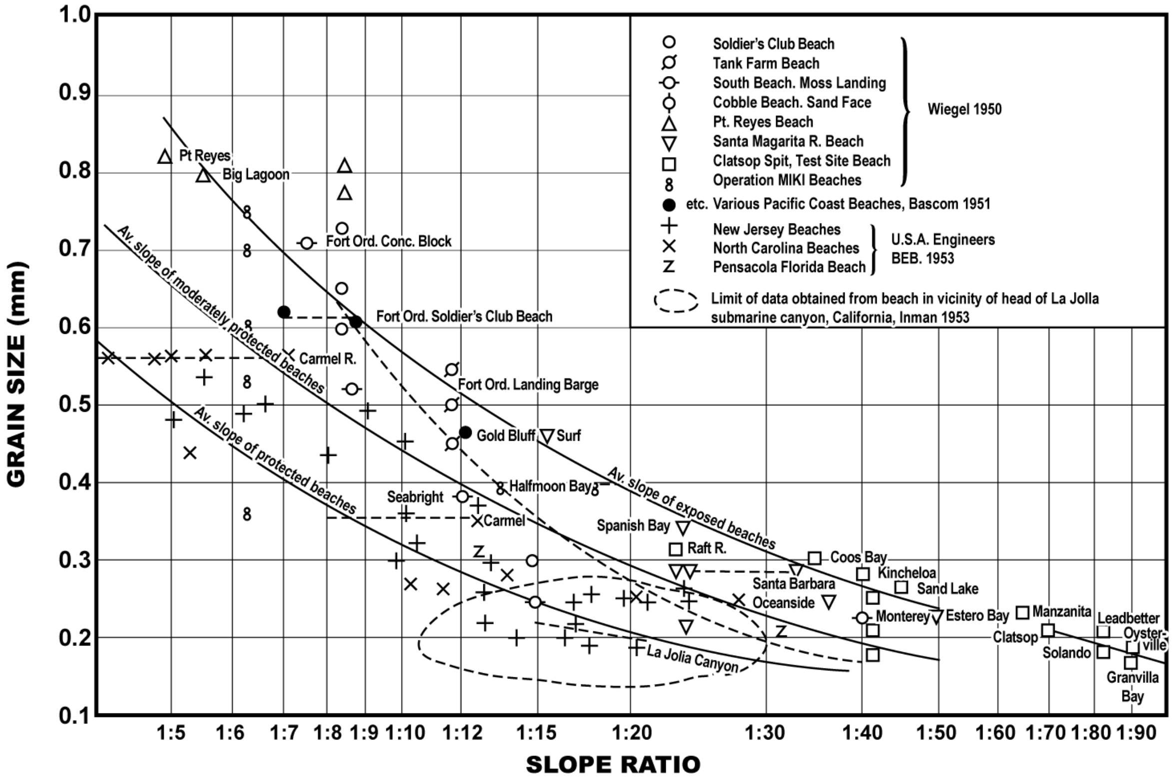
Table III-3-3
Summary of Recommended *A* Values (Units of *A* Parameter are $m^{1/3}$)

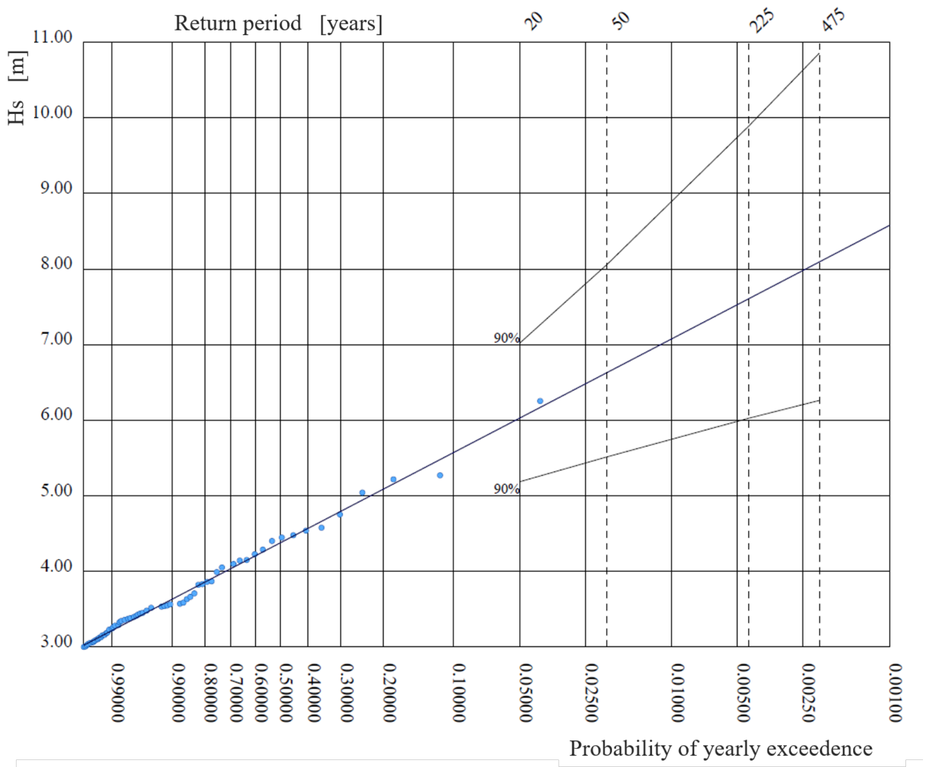
D(mm)	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.1	0.063	0.0672	0.0714	0.0756	0.0798	0.084	0.0872	0.0904	0.0936	0.0968
0.2	0.100	0.103	0.106	0.109	0.112	0.115	0.117	0.119	0.121	0.123
0.3	0.125	0.127	0.129	0.131	0.133	0.135	0.137	0.139	0.141	0.143
0.4	0.145	0.1466	0.1482	0.1498	0.1514	0.153	0.1546	0.1562	0.1578	0.1594
0.5	0.161	0.1622	0.1634	0.1646	0.1658	0.167	0.1682	0.1694	0.1706	0.1718
0.6	0.173	0.1742	0.1754	0.1766	0.1778	0.179	0.1802	0.1814	0.1826	0.1838
0.7	0.185	0.1859	0.1868	0.1877	0.1886	0.1895	0.1904	0.1913	0.1922	0.1931
0.8	0.194	0.1948	0.1956	0.1964	0.1972	0.198	0.1988	0.1996	0.2004	0.2012
0.9	0.202	0.2028	0.2036	0.2044	0.2052	0.206	0.2068	0.2076	0.2084	0.2092
1.0	0.210	0.2108	0.2116	0.2124	0.2132	0.2140	0.2148	0.2156	0.2164	0.2172

Notes:
(1) The *A* values above, some to four places, are not intended to suggest that they are known to that accuracy, but rather are presented for consistency and sensitivity tests of the effects of variation in grain size.
(2) As an example of use of the values in the table, the *A* value for a median sand size of 0.24 mm is: $A = 0.112\ m^{1/3}$. To convert *A* values to $feet^{1/3}$ units, multiply by $(3.28)^{1/3} = 1.49$.

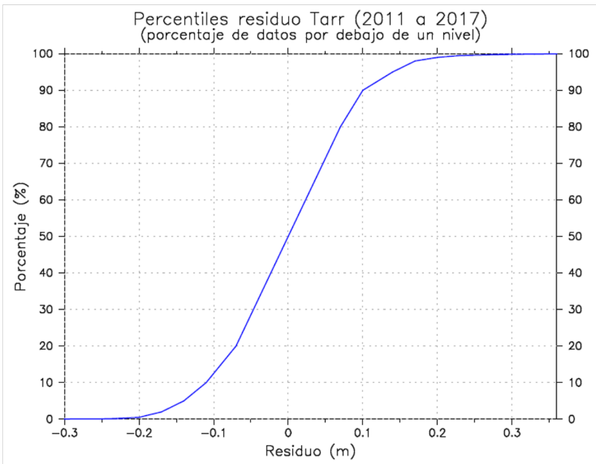
B Beach slope VS grain size (Wiegel 1965)



C Wave data (Puertos del Estado, Ministerio de Fomento 2004-17) (Puertos del Estado, Direccion Tecnica 2019)



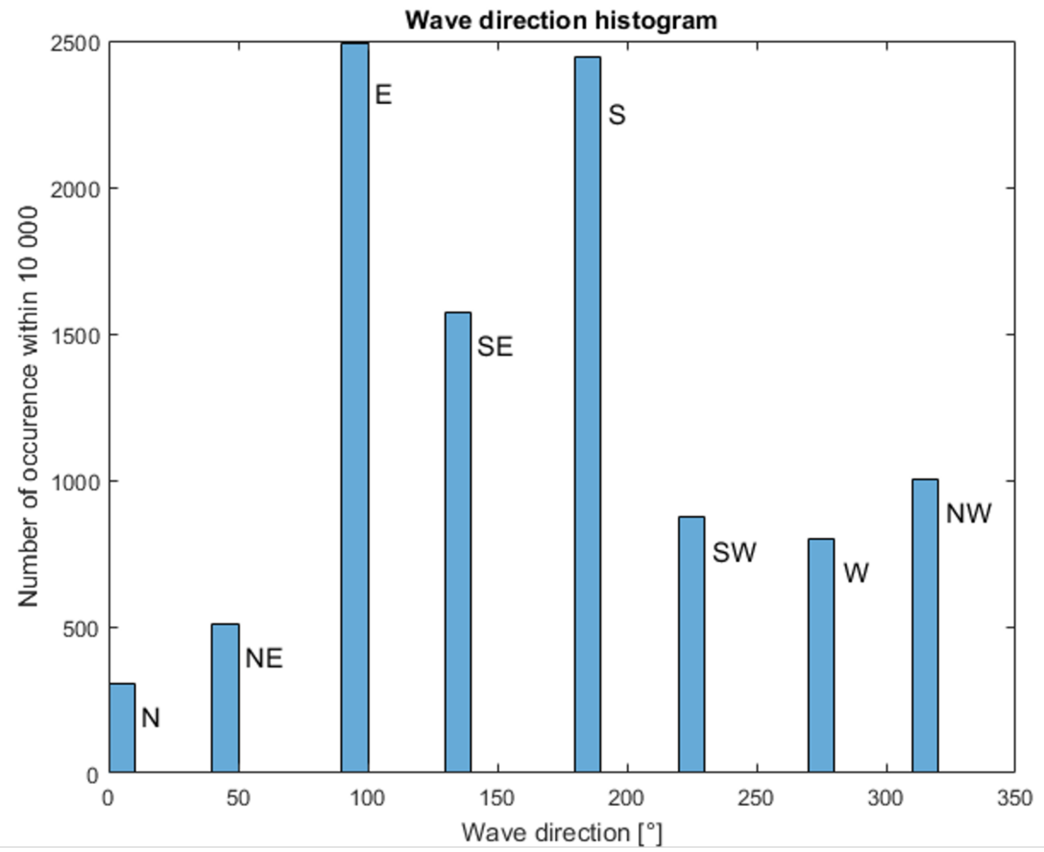
Minimum number of days between peaks	5
Threshold exceeded	3
Mean number of peak within a year (λ)	6.53
Weibull distribution parameters	A = 3.02 B = 0.59 C = 0.97
Relation between wave height [m] and period [s]	$T_P = 3{,}74 H_S^{0.55}$

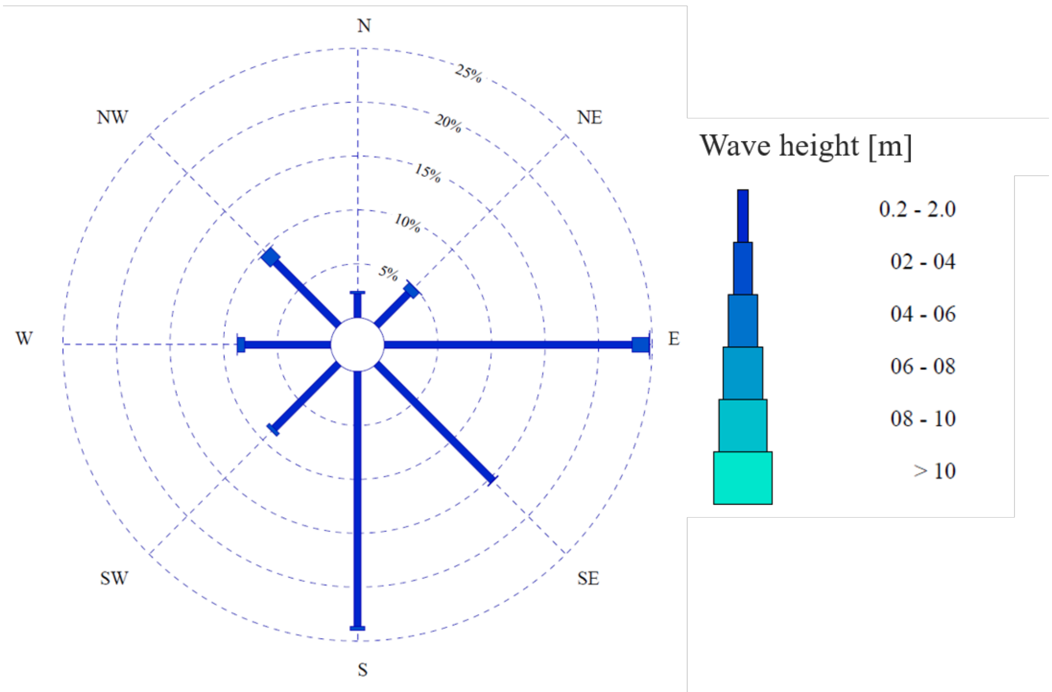


Residuo (m)	% acumulado
-0.30	0.05
-0.25	0.10
-0.23	0.20
-0.20	0.50
-0.19	1.00
-0.17	2.00
-0.14	5.00
-0.11	10.00
-0.07	20.00
0.00	50.00
0.07	80.00
0.10	90.00
0.14	95.00
0.17	98.00
0.20	99.00
0.23	99.50
0.29	99.80
0.33	99.90
0.36	99.95

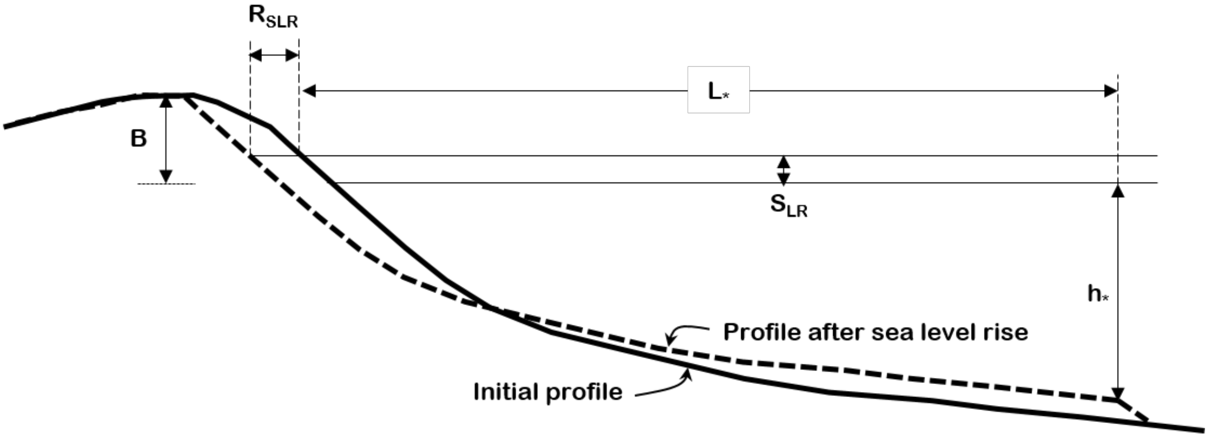
Cumulated frequencies of hourly meterological residual

D Generation of wave direction (Puertos del Estado, Ministerio de Fomento 2004-17)

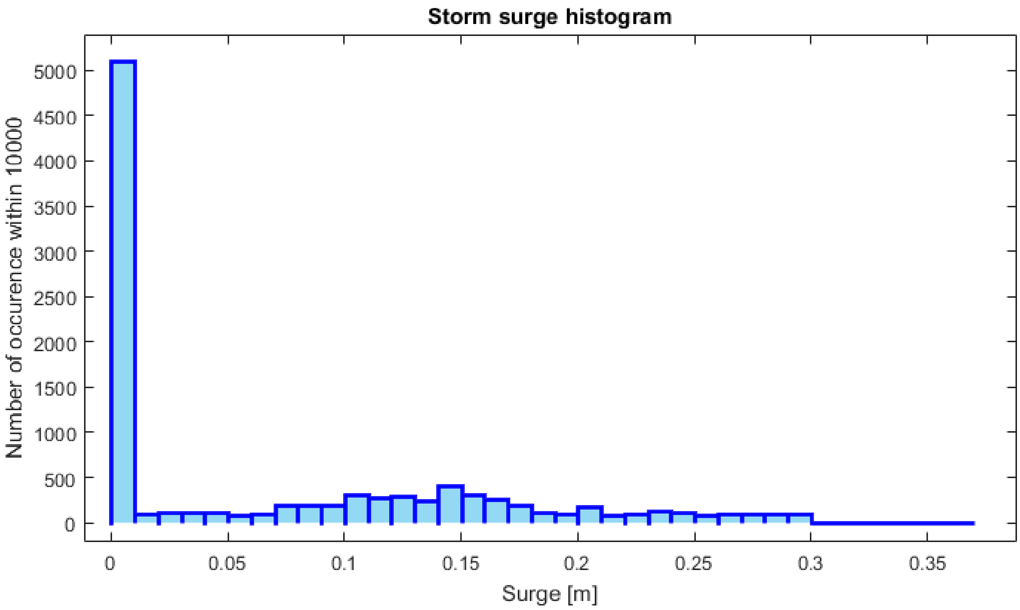




E Bruun rule diagram, adapted from the Scientific Committee on Ocean Research (1991)



F Surge frequencies



G Example of selected storms

Generation between 2000 - 2006

Year	Day	Hs [m]	Tp [s]	Dir. [deg]	Surge [m]	Duration [hrs]
2000	114	3.14	7.83	90	0.12	24
2000	133	3.11	1.02	90	0.14	24
2000	186	3.72	7.18	180	0.20	24
2000	226	3.83	7.90	135	0.18	24
2000	274	3.51	7.85	315	0.18	24
2000	296	3.27	7.03	90	0.11	24
2001	75	3.32	7.54	180	0.22	24
2001	226	3.03	6.88	135	0.07	24
2001	314	4.24	7.73	180	0.20	24
2001	330	3.69	7.34	90	0.13	24
2002	58	3.77	7.38	180	0.12	24
2002	150	3.97	7.03	135	0.13	24
2002	246	4.21	7.00	180	0.10	24
2003	39	3.32	7.08	90	0.07	24
2003	146	3.83	9.22	315	0.16	24
2003	181	3.42	7.43	90	0.08	24
2003	229	3.72	9.89	90	0.24	24
2003	244	3.50	7.32	135	0.18	24
2003	274	3.05	6.88	90	0.16	24
2004	20	3.16	7.89	225	0.04	24
2004	161	3.93	7.21	135	0.09	24
2004	215	3.15	7.61	90	0.14	24
2004	229	3.13	7.35	135	0.26	24
2005	28	3.37	9.04	225	0.03	24
2005	48	4.74	7.51	90	0.07	24
2005	79	3.65	7.05	0	0.17	24
2005	123	3.17	7.49	225	0.05	24
2005	303	3.11	9.94	180	0.12	24
2005	358	3.08	7.37	135	0.09	24
2006	159	4.02	8.13	90	0.12	24
2006	180	3.21	6.90	270	0.19	24
2006	278	3.08	8.81	135	0.26	24
2006	346	3.56	8.29	135	0.08	24
2006	362	3.14	7.57	180	0.06	24

H Example of Casagrande test (from Rosati et al. 2009)

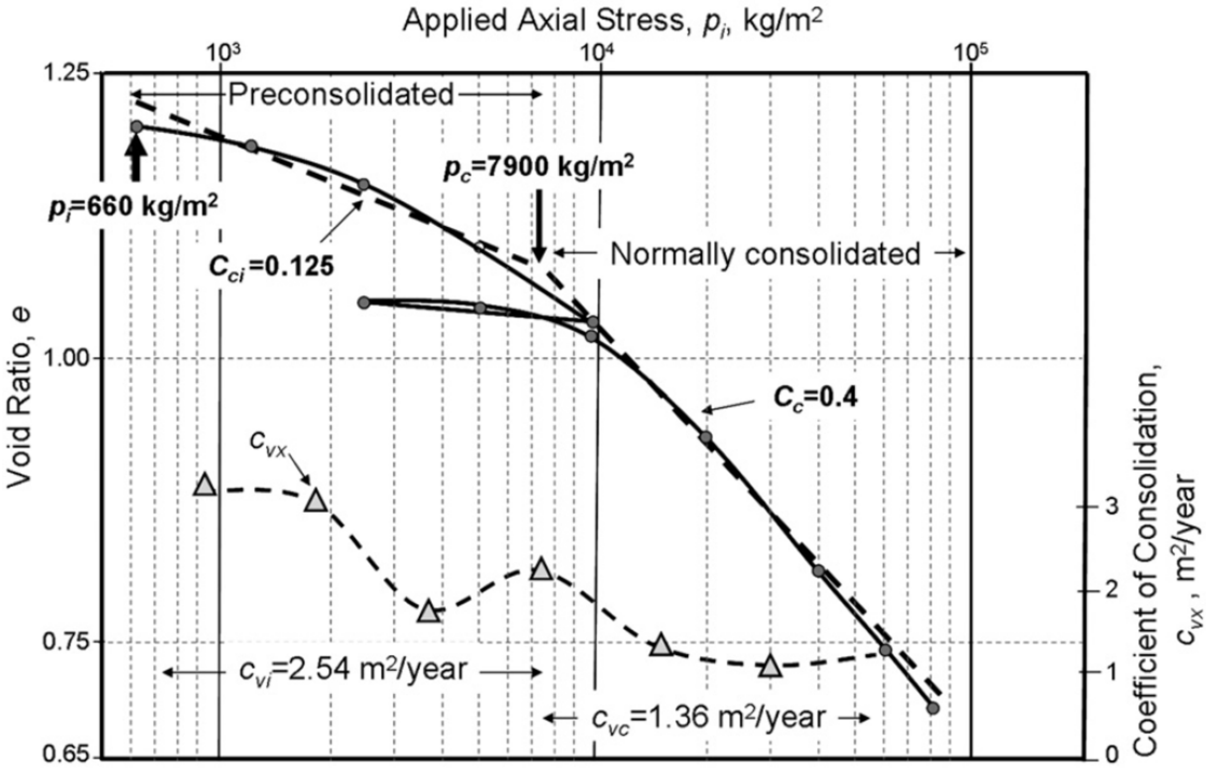


Fig. 4. Casagrande consolidation test from Chaland Headland, Louisiana.

I Percentage of consolidation VS time factor (Liu and Evett 2004)

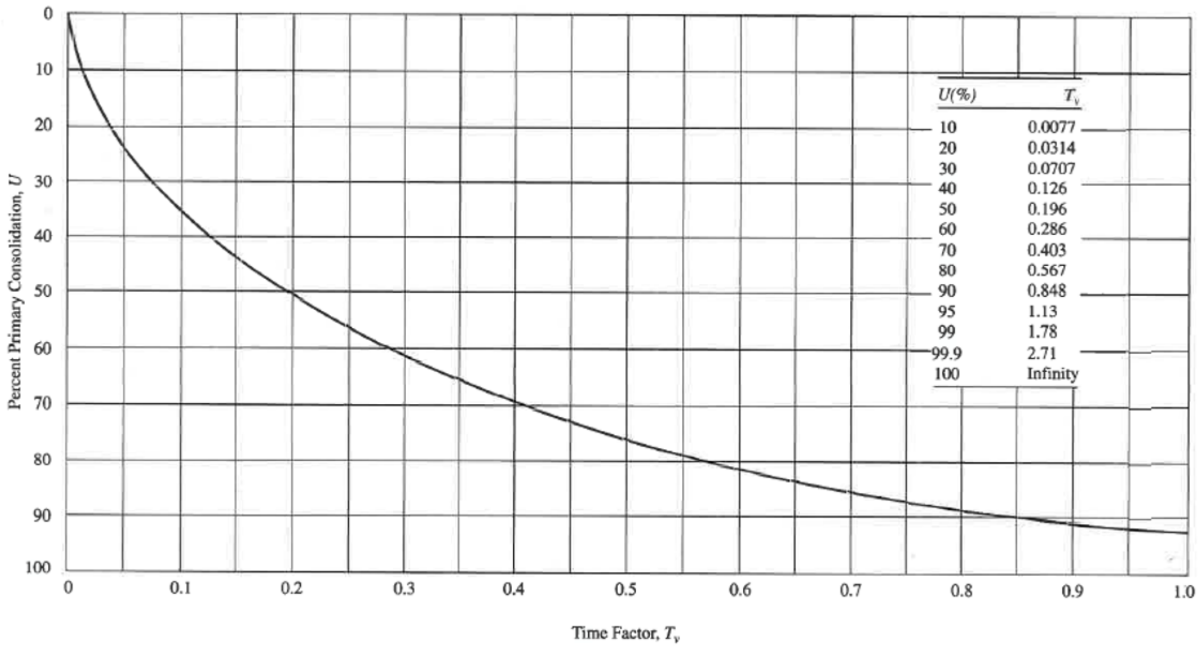


FIGURE 7–18 Time factor as a function of percentage of consolidation (Teng, 1962).

Teng, W. C., *Foundation Design*, Prentice Hall, Englewood Cliffs, NJ, 1962.

J Parameters of storms causing breaching

Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)
2021	144	4.20900601	8.244614478	1.570796327	0.115392849	24
2022	213	4.01732772	8.035947595	3.926990817	0.208113376	24
2022	312	6.12830744	10.13698728	1.570796327	0.150618544	24
2023	71	3.84828346	7.848171454	1.570796327	0.296815788	24
2023	349	4.9756646	9.03940211	3.926990817	0.170997114	24
2025	229	5.65862706	9.70203176	1.570796327	0.257083942	24
2028	300	4.4757562	8.528018507	5.497787144	0.070599704	24
2030	65	4.31942114	8.362875945	2.35619449	0.107257386	24
2030	333	5.629947	9.674955381	3.141592654	0.100455613	24
2032	87	4.8625826	8.925826646	3.926990817	0.251304162	24
2033	69	4.95104929	9.014779107	0	0.161110663	24
2033	222	4.3919847	8.439856299	1.570796327	0.160719557	24
2037	342	4.57505792	8.631568675	1.570796327	0.127543809	24
2039	18	4.44923426	8.500187435	5.497787144	0.128267353	24
2039	95	5.94955847	9.973284491	1.570796327	0.20619143	24
2056	275	5.30664226	9.365317347	3.141592654	0.109629979	24
2058	161	5.3332573	9.391122322	1.570796327	0.252243051	24
2061	340	5.22346956	9.284298385	3.141592654	0.278043849	24
2062	158	4.89471146	8.958215478	1.570796327	0.160455087	24
2064	86	5.5495734	9.598743403	1.570796327	0.10635572	24
2067	135	5.12340146	9.186048109	2.35619449	0.204905517	24
2070	332	4.89975219	8.963288305	5.497787144	0.156605245	24
2112	158	6.86789104	10.79255996	4.71238898	0.291343687	24

K Parameters of storms generated for a simulation of 100 years (2020-2120)

Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)	Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)	Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)	Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)
2020	103	3.075	6.938	0.785	0.090	24	2033	69	4.951	9.015	0.000	0.161	24	2048	201	3.213	7.106	0.785	0.101	24	2061	121	3.181	7.068	0.785	0.112	24
2020	137	3.901	7.908	1.571	0.165	24	2033	95	3.222	7.117	3.142	0.132	24	2049	117	3.065	6.925	5.498	0.103	24	2061	252	3.047	6.902	1.571	0.283	24
2020	201	3.703	7.684	3.142	0.200	24	2033	222	4.392	8.440	1.571	0.161	24	2049	144	3.293	7.204	3.142	0.292	24	2061	340	5.223	9.284	3.142	0.278	24
2020	305	3.535	7.490	1.571	0.160	24	2034	329	3.200	7.091	4.712	0.242	24	2049	335	3.359	7.283	3.142	0.130	24	2062	137	3.365	7.289	3.142	0.209	24
2021	74	3.177	7.062	3.142	0.023	24	2034	364	3.365	7.290	3.142	0.144	24	2050	140	3.038	6.892	2.356	0.137	24	2062	158	4.895	8.958	1.571	0.160	24
2021	138	3.328	7.246	1.571	0.129	24	2035	27	3.034	6.886	3.927	0.123	24	2050	229	3.034	6.887	3.142	0.097	24	2063	257	4.137	8.167	3.927	0.096	24
2021	144	4.209	8.245	1.571	0.115	24	2035	148	3.871	7.873	5.498	0.103	24	2050	338	3.659	7.634	1.571	0.159	24	2063	307	3.133	7.009	0.785	0.110	24
2021	173	3.923	7.932	5.498	0.120	24	2035	279	3.191	7.080	1.571	0.022	24	2051	265	3.198	7.088	1.571	0.131	24	2064	86	5.550	9.599	1.571	0.106	24
2021	204	3.300	7.212	1.571	0.297	24	2035	298	3.313	7.227	2.356	0.204	24	2051	321	3.819	7.815	0.000	0.105	24	2064	223	3.873	7.876	5.498	0.101	24
2022	202	3.144	7.023	3.142	0.094	24	2036	31	4.019	8.037	1.571	0.152	24	2051	360	3.524	7.478	3.927	0.155	24	2064	265	3.156	7.037	3.142	0.285	24
2022	213	4.017	8.036	3.927	0.208	24	2036	201	3.041	6.895	5.498	0.162	24	2052	69	3.047	6.902	1.571	0.142	24	2065	96	3.834	7.833	2.356	0.153	24
2022	312	6.128	10.137	1.571	0.151	24	2037	248	3.198	7.088	3.927	0.076	24	2052	122	4.043	8.065	3.142	0.036	24	2065	184	3.958	7.970	2.356	0.085	24
2023	71	3.848	7.848	1.571	0.297	24	2037	342	4.575	8.632	1.571	0.128	24	2052	236	3.250	7.152	2.356	0.294	24	2065	303	3.642	7.614	3.927	0.266	24
2023	90	3.106	6.975	3.142	0.111	24	2038	12	3.830	7.827	3.142	0.094	24	2052	330	3.694	7.674	3.142	0.152	24	2066	127	3.244	7.145	5.498	0.032	24
2023	217	3.742	7.728	2.356	0.229	24	2038	70	3.063	6.923	1.571	0.061	24	2054	88	3.034	6.886	1.571	0.104	24	2066	240	3.182	7.068	2.356	0.169	24
2023	349	4.976	9.039	3.927	0.171	24	2038	84	3.612	7.579	5.498	0.168	24	2054	166	3.678	7.656	0.785	0.234	24	2067	135	5.123	9.186	2.356	0.205	24
2024	357	3.279	7.186	3.142	0.128	24	2038	191	3.074	6.936	3.142	0.103	24	2054	292	3.292	7.203	1.571	0.155	24	2067	154	3.413	7.347	3.142	0.269	24
2025	76	3.641	7.613	4.712	0.131	24	2039	18	4.449	8.500	5.498	0.128	24	2054	306	3.348	7.270	1.571	0.217	24	2067	243	3.867	7.870	3.142	0.149	24
2025	82	3.153	7.033	2.356	0.158	24	2039	95	5.950	9.973	1.571	0.206	24	2055	53	3.181	7.068	2.356	0.033	24	2067	344	3.978	7.992	1.571	0.128	24
2025	92	3.188	7.077	5.498	0.119	24	2039	174	3.468	7.412	1.571	0.189	24	2055	120	3.272	7.178	3.927	0.152	24	2068	15	3.036	6.888	1.571	0.195	24
2025	106	3.121	6.994	4.712	0.156	24	2039	289	3.326	7.243	1.571	0.072	24	2055	150	3.808	7.803	2.356	0.104	24	2068	59	3.444	7.383	3.142	0.078	24
2025	218	3.171	7.055	2.356	0.133	24	2040	135	3.486	7.433	2.356	0.145	24	2055	307	3.233	7.131	3.142	0.144	24	2068	107	3.091	6.957	4.712	0.160	24
2025	229	5.659	9.702	1.571	0.257	24	2040	229	3.577	7.538	0.785	0.076	24	2055	323	3.343	7.263	0.785	0.129	24	2068	211	3.788	7.780	1.571	0.136	24
2026	275	3.440	7.378	4.712	0.105	24	2040	336	3.110	6.981	0.000	0.257	24	2056	33	3.610	7.577	1.571	0.110	24	2069	55	3.945	7.956	2.356	0.144	24
2026	362	3.718	7.701	4.712	0.125	24	2041	108	3.642	7.614	1.571	0.139	24	2056	127	3.342	7.263	3.142	0.103	24	2069	83	3.021	6.870	5.498	0.070	24
2027	90	3.628	7.598	1.571	0.117	24	2041	144	3.300	7.213	3.927	0.153	24	2056	174	3.199	7.090	2.356	0.054	24	2069	112	3.117	6.989	3.142	0.184	24
2027	177	3.281	7.189	1.571	0.295	24	2042	181	3.681	7.659	1.571	0.139	24	2056	187	3.361	7.284	1.571	0.244	24	2069	310	3.263	7.167	1.571	0.127	24
2027	214	3.416	7.350	2.356	0.275	24	2042	249	3.110	6.981	1.571	0.142	24	2056	275	5.307	9.365	3.142	0.110	24	2070	23	3.168	7.051	0.000	0.267	24
2028	133	3.517	7.469	5.498	0.134	24	2043	179	3.268	7.174	2.356	0.284	24	2057	76	3.115	6.987	3.142	0.199	24	2070	106	3.149	7.028	3.142	0.115	24
2028	193	3.851	7.851	1.571	0.173	24	2043	258	4.334	8.379	3.142	0.105	24	2057	93	3.069	6.930	3.142	0.159	24	2070	227	3.024	6.873	3.927	0.300	24
2028	248	3.754	7.742	1.571	0.128	24	2043	330	3.652	7.625	5.498	0.170	24	2057	120	3.194	7.084	1.571	0.110	24	2070	313	3.448	7.388	4.712	0.137	24
2028	300	4.476	8.528	5.498	0.071	24	2044	1	3.022	6.871	3.927	0.138	24	2057	325	3.328	7.245	2.356	0.281	24	2070	332	4.900	8.963	5.498	0.157	24
2028	309	3.505	7.456	1.571	0.014	24	2044	66	3.365	7.290	1.571	0.073	24	2058	161	5.333	9.391	1.571	0.252	24	2071	160	3.100	6.968	2.356	0.007	24
2029	61	3.656	7.630	3.142	0.245	24	2044	228	3.385	7.314	5.498	0.155	24	2058	254	3.100	6.969	2.356	0.072	24	2071	347	3.352	7.274	3.927	0.086	24
2029	144	3.250	7.151	5.498	0.076	24	2045	176	3.234	7.132	4.712	0.105	24	2058	330	3.960	7.972	2.356	0.033	24	2072	13	3.713	7.695	3.142	0.059	24
2029	340	3.086	6.950	2.356	0.114	24	2045	210	3.021	6.870	3.142	0.073	24	2058	348	4.600	8.657	4.712	0.045	24	2072	191	3.376	7.303	1.571	0.257	24
2030	65	4.319	8.363	2.356	0.107	24	2046	18	3.469	7.413	1.571	0.153	24	2059	19	3.189	7.077	4.712	0.120	24	2072	197	3.483	7.430	2.356	0.201	24
2030	81	3.060	6.919	5.498	0.142	24	2046	96	3.670	7.646	4.712	0.263	24	2059	66	3.224	7.120	0.785	0.267	24	2072	227	3.084	6.948	0.000	0.097	24
2030	220	3.165	7.049	3.142	0.254	24	2046	102	4.006	8.023	3.142	0.210	24	2059	241	3.643	7.615	1.571	0.031	24	2072	280	3.657	7.631	3.142	0.110	24
2030	323	3.484	7.431	3.142	0.131	24	2046	129	3.712	7.694	1.571	0.032	24	2059	351	3.657	7.631	1.571	0.140	24	2073	100	3.679	7.657	5.498	0.072	24
2030	333	5.630	9.675	3.142	0.100	24	2046	225	4.266	8.306	0.785	0.000	24	2060	61	3.419	7.354	1.571	0.233	24	2073	199	3.114	6.986	3.142	0.068	24
2031	73	3.118	6.991	2.356	0.005	24	2046	263	3.349	7.270	5.498	0.130	24	2060	76	3.089	6.954	3.927	0.080	24	2073	268	3.137	7.014	1.571	0.216	24
2031	161	3.917	7.925	2.356	0.212	24	2047	29	3.241	7.141	3.142	0.113	24	2060	212	3.835	7.833	2.356	0.084	24	2074	101	3.058	6.917	0.785	0.138	24
2031	167	3.402	7.334	3.142	0.138	24	2047	166	3.438	7.376	1.571	0.045	24	2060	270	3.388	7.317	1.571	0.099	24	2074	209	3.113	6.985	3.142	0.137	24
2032	87	4.863	8.926	3.927	0.251	24	2047	176	3.712	7.694	1.571	0.278	24	2060	302	3.706	7.688	1.571	0.159	24	2074	341	3.058	6.916	1.571	0.076	24
2032	209	3.420	7.356	3.927	0.133	24	2048	6	4.119	8.147	1.571	0.014	24	2061	1	3.452	7.392	1.571	0.232	24	2075	62	3.089	6.955	1.571	0.127	24
2032	286	3.711	7.693	3.142	0.229	24	2048	15	3.364	7.288	2.356	0.109	24	2061	72	3.024	6.874	3.142	0.009	24	2075	171	4.255	8.294	1.571	0.107	24

Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)	Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)	Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)	Year	Day of the year	Hs (m)	Tp (s)	Dir (rad)	Surge (m)	Duration (hrs)
2076	24	3.505	7.455	3.142	0.042	24	2091	226	4.438	8.489	3.142	0.088	24	2102	279	3.983	7.998	3.142	0.020	24	2116	232	3.263	7.167	0.000	0.105	24
2076	231	3.995	8.011	3.142	0.048	24	2092	70	3.280	7.187	0.785	0.137	24	2103	181	4.372	8.419	2.356	0.078	24	2116	262	3.717	7.699	0.000	0.012	24
2076	356	3.151	7.032	3.927	0.026	24	2092	94	3.376	7.303	0.785	0.105	24	2103	201	3.237	7.136	5.498	0.174	24	2117	229	3.583	7.546	1.571	0.170	24
2076	363	3.517	7.469	2.356	0.221	24	2092	125	3.209	7.101	3.142	0.162	24	2103	332	5.065	9.129	3.142	0.226	24	2118	307	3.274	7.181	5.498	0.002	24
2077	93	3.361	7.285	2.356	0.100	24	2092	156	3.146	7.025	5.498	0.165	24	2104	20	3.318	7.233	3.142	0.051	24	2119	15	3.561	7.521	1.571	0.154	24
2077	218	4.018	8.037	5.498	0.173	24	2092	181	3.476	7.421	4.712	0.057	24	2104	65	3.048	6.904	1.571	0.155	24	2119	119	3.253	7.156	3.142	0.004	24
2078	157	3.376	7.303	3.927	0.095	24	2092	293	3.031	6.883	2.356	0.078	24	2104	79	4.651	8.710	2.356	0.118	24	2119	231	3.463	7.406	2.356	0.269	24
2078	239	3.106	6.975	1.571	0.126	24	2093	24	3.476	7.421	0.785	0.178	24	2104	140	3.505	7.455	4.712	0.148	24	2119	250	3.209	7.102	3.142	0.122	24
2078	271	3.036	6.889	2.356	0.178	24	2093	238	3.324	7.241	5.498	0.119	24	2104	226	3.063	6.922	4.712	0.062	24	2119	341	3.250	7.152	3.927	0.288	24
2078	341	3.126	7.001	1.571	0.071	24	2093	301	3.416	7.350	4.712	0.224	24	2104	284	3.142	7.019	1.571	0.206	24	2120	284	3.194	7.083	4.712	0.086	24
2079	47	4.763	8.824	3.142	0.143	24	2094	27	3.201	7.092	1.571	0.170	24	2104	311	3.554	7.512	3.142	0.158	24							
2079	277	3.028	6.879	3.142	0.153	24	2094	157	3.557	7.516	3.142	0.165	24	2105	146	3.621	7.590	4.712	0.264	24							
2079	284	4.161	8.193	0.000	0.134	24	2095	197	3.610	7.577	1.571	0.122	24	2105	158	5.316	9.375	3.927	0.136	24							
2080	326	4.067	8.091	1.571	0.092	24	2095	234	3.570	7.531	2.356	0.218	24	2105	168	3.820	7.817	1.571	0.219	24							
2081	20	3.027	6.878	0.785	0.091	24	2095	285	3.035	6.887	0.785	0.127	24	2105	253	3.721	7.705	3.927	0.247	24							
2081	158	4.443	8.493	3.142	0.105	24	2095	330	3.070	6.931	2.356	0.026	24	2106	41	5.160	9.223	2.356	0.091	24							
2082	55	4.275	8.316	0.785	0.147	24	2096	134	3.148	7.027	4.712	0.098	24	2106	214	3.275	7.182	1.571	0.291	24							
2082	112	3.245	7.145	3.142	0.150	24	2096	199	3.052	6.909	1.571	0.290	24	2106	283	3.281	7.189	2.356	0.126	24							
2082	259	3.449	7.389	3.142	0.214	24	2097	19	4.069	8.092	2.356	0.172	24	2107	89	3.361	7.285	3.927	0.181	24							
2082	319	3.229	7.127	1.571	0.116	24	2097	34	3.527	7.481	1.571	0.081	24	2107	101	3.765	7.754	2.356	0.119	24							
2082	326	3.582	7.545	1.571	0.128	24	2097	94	3.369	7.294	1.571	0.145	24	2107	223	4.446	8.496	2.356	0.103	24							
2082	353	3.140	7.017	3.927	0.135	24	2097	115	3.106	6.975	3.142	0.162	24	2107	308	3.664	7.639	3.142	0.156	24							
2083	124	3.472	7.416	1.571	0.041	24	2097	225	3.361	7.285	3.142	0.035	24	2108	36	4.919	8.982	2.356	0.146	24							
2083	285	3.216	7.111	5.498	0.265	24	2098	22	3.087	6.952	3.142	0.099	24	2108	122	4.227	8.264	2.356	0.131	24							
2084	162	3.314	7.229	5.498	0.011	24	2098	51	3.072	6.933	5.498	0.153	24	2108	316	3.931	7.941	1.571	0.087	24							
2084	223	4.509	8.563	1.571	0.203	24	2098	294	4.063	8.086	1.571	0.141	24	2108	362	3.127	7.001	3.142	0.146	24							
2084	249	3.076	6.938	1.571	0.285	24	2098	319	3.179	7.065	5.498	0.011	24	2109	84	3.287	7.196	4.712	0.038	24							
2085	12	3.204	7.096	3.142	0.022	24	2098	330	3.508	7.458	5.498	0.271	24	2110	142	3.697	7.677	3.927	0.077	24							
2085	216	3.312	7.226	3.927	0.094	24	2099	116	3.157	7.039	3.142	0.300	24	2110	198	3.195	7.085	4.712	0.108	24							
2085	355	3.240	7.140	4.712	0.157	24	2099	143	3.152	7.032	4.712	0.246	24	2110	243	3.028	6.878	2.356	0.034	24							
2086	90	3.359	7.283	3.927	0.114	24	2099	217	3.470	7.414	5.498	0.065	24	2110	326	3.603	7.569	2.356	0.081	24							
2086	108	3.466	7.409	3.927	0.063	24	2099	299	3.159	7.040	4.712	0.132	24	2110	349	3.107	6.977	5.498	0.104	24							
2086	173	3.184	7.071	1.571	0.157	24	2099	330	3.235	7.134	1.571	0.110	24	2111	137	3.425	7.361	1.571	0.135	24							
2087	245	3.422	7.358	5.498	0.143	24	2100	19	3.063	6.922	5.498	0.110	24	2111	306	3.413	7.346	4.712	0.105	24							
2087	360	4.301	8.344	3.142	0.124	24	2100	81	3.299	7.211	0.785	0.128	24	2111	348	3.422	7.358	3.142	0.110	24							
2088	241	3.150	7.029	3.142	0.075	24	2100	100	3.565	7.524	4.712	0.005	24	2112	158	6.868	10.793	4.712	0.291	24							
2089	22	3.315	7.230	1.571	0.055	24	2100	163	3.804	7.799	1.571	0.085	24	2112	218	4.056	8.079	3.142	0.282	24							
2089	81	3.607	7.573	3.142	0.202	24	2100	267	4.477	8.529	3.927	0.257	24	2112	275	5.735	9.774	3.927	0.123	24							
2089	219	4.550	8.606	1.571	0.051	24	2100	297	3.320	7.236	3.142	0.065	24	2113	78	3.152	7.033	1.571	0.276	24							
2090	78	3.100	6.969	1.571	0.163	24	2101	57	3.259	7.163	0.785	0.038	24	2113	345	3.451	7.392	4.712	0.125	24							
2090	150	3.646	7.618	0.785	0.005	24	2101	205	3.077	6.940	1.571	0.280	24	2114	121	3.685	7.663	5.498	0.091	24							
2090	211	3.551	7.509	1.571	0.122	24	2101	215	3.471	7.415	3.927	0.139	24	2114	200	3.442	7.381	5.498	0.113	24							
2090	339	3.998	8.015	1.571	0.229	24	2101	332	3.332	7.250	3.927	0.163	24	2115	34	4.136	8.165	3.927	0.010	24							
2091	35	3.030	6.881	3.142	0.142	24	2102	42	3.029	6.880	0.785	0.074	24	2115	295	3.111	6.981	5.498	0.151	24							
2091	64	3.844	7.843	3.927	0.042	24	2102	61	4.204	8.239	3.142	0.254	24	2116	31	4.131	8.160	3.142	0.262	24							
2091	92	5.041	9.104	1.571	0.037	24	2102	192	3.254	7.157	3.142	0.162	24	2116	39	3.131	7.007	3.142	0.114	24							
2091	212	3.291	7.202	3.927	0.083	24	2102	235	3.683	7.660	3.142	0.196	24	2116	186	3.165	7.048	3.142	0.141	24							

L Matlab code

L.1 Example of main simulation, for long term impact of storms

```
%--------------------------------BARRIER BEACH CROSS-SHORE MODEL--------------------------------
%MAIN EXECUTIVE FILE
%Ludovic Le Coz, June-July 2019
%---------------------------------------------------------------------------------------
%Loading of the measured beach profile, asking the user
profile_name = uigetfile;
data_range = input('Enter the data range used in the excel file (H5:I417):\n','s');
profile_ini = xlsread(profile_name,data_range);
%'ShoreProfile_P5f00362_06-Sep-2017.xlsx'
%'A6:B135'
%---------------------------------------------------------------------------------------
%Profile characteristics-------------------------------------------
%A = 0.065; %equilibruim constant
d50_mm = 0.25; %mean grain diameter
rho_s = 2560; %sand density in kg/m3
A = get_A(d50_mm, rho_s, '4', '1');
% nb_iter = 5;
option =1;
% profile = get_simplified_profile(profile_ini, A, nb_iter);
phi = degtorad(40); %sand friction angle in rad
res = 0.001;
option_beta = '2'; %1 slope calculation, 2 constant value from table
option_runup = '1'; %1 Stockdon, 2 Hughes
gamma = 0.78;
%Depth of closure from initial data set
[ini_n,~] = size(profile_ini);
i = 1;
while std(profile_ini(i:ini_n,2))> 0.3
    i = i+1;
end
doc_z = profile_ini(i,2);
%---------------------------------------------------------------------------------------
```

```
%Storms characteristics--------------------------------------------
wA = 3.02;
wB = 0.59;
wC = 0.97;
wD = 3.74;
wE = 0.55;
wlambda = 6.53;
wpd = [0 0.07 0.1 0.14 0.17 0.2 0.23 0.29 0.33 0.36 0.6 ;0.5 0.8 0.9 0.95 0.98 0.99 0.995 0.998 0.999 0.9995 1];
wTd = 24;
yr = 2020:1:2120;
profile = get_simplified_profile(profile_ini, A, 1);
doc_x = find_x(doc_z, profile, 1);
% dune_height = 1.5;
% profile(1,4,2) = dune_height;
% profile(1,6,2) = dune_height;
% profile(1,2,3) = dune_height;
% profile(1,4,3) = dune_height;
% profile(1,6,3) = dune_height;
% profile(1,2,4) = dune_height;
% profile(1,6,4) = dune_height;
% fprintf('The new dune height is %4.2f meters.\n',dune_height);

storms = [];
for y = 1:length(yr)
    storms_yr = storm_generation(wA, wB, wC, wD, wE, wlambda, wpd, yr(y), wTd); %storms_yr = [yr, day, Hs, Tp, alpha, s, Td]
    storms = [storms; storms_yr];
    [strm_nb, ~] = size(storms_yr);
    nb_iter = strm_nb+1;
    profile = cat(1,profile, zeros(strm_nb,7,5));
end
% storms = storms(1:3,:);
[strm_nb, ~] = size(storms);
sea_level = zeros(1,strm_nb+1);
D_retreat_slr = zeros(1,strm_nb+1);
date = zeros(1,strm_nb+1);
date(1) = yr(1);

% ------------------------------------------------------------------
```

```
%Sea level rise_______________________________________________________
for i=2:strm_nb+1
    date(i) = storms(i-1,1)+(storms(i-1,2)/365);
    [R_bruun, profile_int, lvl] = slr(doc_x, doc_z, date(i), profile, i-1);
    D_retreat_slr(i) = R_bruun+D_retreat_slr(i-1);
    profile(i,:,:) = profile_int;
    sea_level(i+1)=lvl;
end
[R_bruun, ~, ~] = slr(doc_x, doc_z, 2000, profile, 1);
D_retreat_slr(1)=D_retreat_slr(2)-R_bruun;
figure('Name','Bruun rule')
plot(date,D_retreat_slr,'b','linewidth',2)
legend('SLR retreat')
xlabel('Time [yr]')
ylabel('Retreat [m]')
title('Storms impact on retreat')

style = [];
breaches = zeros(1,strm_nb);
D_retreat_storms = zeros(1,strm_nb);
D_width_storms = zeros(1,strm_nb);
D_width_add = zeros(2,strm_nb);
D_height_storms = zeros(1,strm_nb);

for i=1:strm_nb
    H0 = storms(i,3);
    T0 = storms(i,4);
    alpha0 = storms(i,5);
    S = storms(i,6);
    wTd = storms(i,7)*60*60;
    [Ru, beta] = run_up(H0, T0, alpha0, gamma, profile, i, option_beta, option_runup, S);
    [Hb, db] = breaking(H0, T0, alpha0, gamma, profile, i);

    if S+Ru> profile(i,4,3) %Case of overwash
        [qsw, qd, type] = overwash_volumes(profile, Ru, S, db, beta, i);
        Qsw = qsw*wTd;
        Qd = qd*wTd;
        if type == 'Inundation'
            style = [style 'OVERWASH Inundation'];
        elseif type == 'Run up    '
            style = [style 'OVERWASH Run up    '];
        end
```

```
            [R, z, w, H, profile_int2, breach] = overwash (Qsw, Qd,
                profile, phi, S, i, res);
            breaches(i) = breach;
            if breach
                profile(i+1,:,:) = profile(i,:,:);
            else
                profile(i+1,:,:) = profile_int2;
                D_retreat_storms(i) = R;
                D_width_storms(i) = R;
                D_width_add(:,i) = [w; H];
                D_height_storms(i) = z;
            end
        else %Case of erosion
            style = [style 'EROSION                 '];
            B = profile(i,4,3)-profile(i,2,5); %Dune height
            m=0;
            C1 = 30;
            Ts = ( C1*Hb^(3/2)/(sqrt(9.81)*A^3) ) /( 1 + abs(db(2))/
                B + m*db(1)/abs(db(2)) );
            [R, profile_int2, breach] = erosion2(Ts, wTd, S, db,
                profile, i);
            breaches(i) = breach;
            if breach
                profile(i+1,:,:) = profile(i,:,:);
            else
                profile(i+1,:,:) = profile_int2;
                D_retreat_storms(i) = R;
                D_width_storms(i) = R;
            end
        end
end

figure()
[u,v] = plot_profile(profile, res,1);
plot(u,v)
hold
[u2,v2] = plot_profile(profile_int, res,1);
plot(u2,v2)
```

L.2 Example of main simulation, single storm approach and settlement

```
%---------------------------------BARRIER BEACH CROSS-SHORE MODEL---------------------------------
%MAIN EXECUTIVE FILE
%Ludovie Le Coz, May 2019
%---------------------------------------------------------------------------------------------
%Loading of the measured beach profile, asking the user
profile_name = uigetfile;
data_range = input('Enter the data range used in the excel file (H5:I417):\n','s')
profile_ini = xlsread(profile_name,data_range);
'ShoreProfile_P5f00362_06-Sep-2017.xlsx'
%'A6:B135'
%---------------------------------------------------------------------------------------------
%Profile characteristics------------------------------------------------
A = 0.065; %equilibruim constant
d50_mm = 0.25; %mean grain diameter
rho_s = 2560; %sand density in kg/m3
A = get_A(d50_mm, rho_s, '4', '1');
nb_iter = 2;
option =1;
profile = get_simplified_profile(profile_ini, A, nb_iter);
res = 0.1;
t = 2;
[X,Z] = plot_profile(profile, res, t-1);
figure('Name','Geometrical modelling');
plot (X, Z)
title('Modelled profile')
xlabel('Distance offshore [m] (chainage)')
ylabel('Elevation [m]')
hold
plot(profile_ini(:,1),profile_ini(:,2),'-x')
legend('Modelled profile', 'Field data profile')

%Geology characteristics------------------------------------------------
phi = degtorad(40); %sand friction angle in rad

%Hydraulic
```

```
characteristics_________________________________________
% alpha0=0;
% H0=4;
% T0=8;
A = 3.02;
B = 0.59;
C = 0.97;
D = 3.74;
E = 0.55;
lambda = 6.53;
pd = [0 0.07 0.1 0.14 0.17 0.2 0.23 0.29 0.33 0.36 0.6 ;0.5 0.8 0.9 0.95 0.98 0.99 0.995 0.998 0.999 0.9995 1];
storms_yr = storm_generation(A, B, C, D, E, lambda, pd) % storms_yr = [day, Hs, Tp, alpha, s, Td]
gamma = 0.78;
[Hb, db, xb] = breaking(storms_yr(1,2), storms_yr(1,3), storms_yr(1,4), gamma, profile, t-1);
% ------------------------------------------------------------------

% Run_____________________________________________________________

%EROSION AND OVERWASH
profile = get_simplified_profile(profile_ini, A, nb_iter);
%S = 0.3;
S = storms_yr(1,5);
beta_option = '2'; %1 slope calculation, 2 constant value from table
runup_option = '1'; %1 Stockdon, 2 Hughes
%Rmq : comparing with real profile estimation of the slope, the method 2
%for beta seems more appropriate. Moreover, the method 1 for R gives
%smaller values than the method 2
[R, beta] = run_up(H0, T0, alpha0, gamma, profile, t-1, beta_option, runup_option, S);
%Td = 10*60*60;
Td = storms_yr(1,6)*60*60;
if S+R> profile(t-1,4,3) %Case of overwash
    [qsw, qd, type] = overwash_volumes(profile, R, S, db, beta, t);
    Qsw = qsw*Td;
%     Qd = qd*Td;
```

```
    Qd = 15;
    tic
    profile = response_overwash (Qsw, Qd, profile, t, res, phi);
    toc
    [X,Z] = plot_profile(profile, res, t-1);
    figure('Name','Overwash');
    plot (X, Z)
    title(['Profile reshaping after ', type, ' overwash'])
    xlabel('Distance offshore [m] (chainage)')
    ylabel('Elevation [m]')
    hold
    [X1,Z1] = plot_profile(profile, res, t);
    plot (X1, Z1)
    legend('Profile (t-1)', 'Profile after overwash (t)')
    dim =[.92 .5 .1 .2];
    str = sprintf('A=%4.2f m^(1/3)\nalpha=%4.2fdeg \nH0=%4.2f m
        \nT0=%4.2f s \nTd =%4.2f hrs \nR=%4.2f m \nQsw=%5.3f m^3
        \nQd=%5.3f m^3', A, alpha0, H0, T0, Td/3600, R, Qsw, Qd);
    annotation('textbox',dim,'String',str,'FitBoxToText','on');
    toc
else %Case of erosion
    B = profile(t-1,2,3); %Dune height
    m=0;
    C1 = 320;
    Ts = ( C1*Hb^(3/2)/(sqrt(9.81)*A^3) ) /( 1 + abs(db(2))/B +
        m*db(1)/abs(db(2)) );
    fprintf('The characteristic time response is %4.2f hours.\n'
        ,Ts/3600);
    [profile, R] = response_erosion (Ts, Td, S, db, profile, t,
        res, option);
    [X1,Z1] = plot_profile(profile, res, t-1);
    [X2,Z2] = plot_profile(profile, res, t);
    figure('Name','Erosion');
    plot (X1,Z1,'b')
    title('Profile reshaping after erosion')
    xlabel('Distance offshore [m] (chainage)')
    ylabel('Elevation [m]')
    hold
    plot(X2,Z2,'-.r','linewidth',2)
    legend('Profile (t-1)', 'Profile after erosion (t)')
    dim =[.92 .5 .1 .2];
    str = sprintf('A=%4.2f m^(1/3)\nalpha=%4.2fdeg \nH0=%4.2f m
        \nT0=%4.2f s \ngamma =%4.2f \nTs=%4.2f hrs \nTd=%4.2f hrs
         \nR=%4.2f m', A, alpha0, H0, T0, gamma, Ts/3600, Td
        /3600, R);
    annotation('textbox',dim,'String',str,'FitBoxToText','on');
```

```
end

%SETTLMENT
t_btw_storm = 31*24*60*60;
Pc = 7900;
Cc = 0.4;
Pi = 660;
Cci = 0.125;
Cv = 2;
e0 = 1.23;
H = 1;
res= 0.01;
t =2;
z_layer = -15;
[Xset,Zset] = settlment(profile, t_btw_storm, Pc, Cc, Pi, Cci, Cv, e0, H, res, t, z_layer, rho_s);
[X,Z] = plot_profile(profile, res, t);
figure('Name','Settlment');
plot (X,Z,'b')
title('Profile reshaping after settlment')
xlabel('Distance offshore [m] (chainage)')
ylabel('Elevation [m]')
hold
plot(Xset,Zset,'-.r','linewidth',2)
plot (X,Z-Zset, ':')
legend('Initial profile', 'Profile after settlment')
dim =[.92 .5 .1 .2];
str = sprintf('A=%4.2f m^(1/3)\nTime btwn storm=%4.2f days \nPc=%4.2f kg/m^2 \nCc=%4.2f \nPi =%4.2f kg/m^2\nCci=%4.2f \nCv=%4.2f m^2/yr \ne0=%4.2f \nThickness=%4.2f m \nDepth=%4.2f m', ...
    A, t_btw_storm/(3600*24), Pc, Cc, Pi, Cci, Cv, e0, H, z_layer);
annotation('textbox',dim,'String',str,'FitBoxToText','on');

%SEAL LEVEL RISE
s = 0.45; %sea level rise in meters in 2100 RCP 4.5
Hs = 3.2; %12h exceedence in a year, from Tarragona buoy
L_L = 3333; %the active length lagoon size, from Guillen thesis, Bruun rule adapted by Dean & Maurmeyer 83
[Xinf, Zinf] = slr(s, profile, res, T0, Hs, L_L);
[X,Z] = plot_profile(profile, res, 1);
figure('Name','Sea level rise');
plot (X,Z)
title('Profile reshaping after sea level rise - Bruun rule')
xlabel('Distance offshore [m] (chainage)')
```

```
ylabel('Elevation [m]')
hold
plot(Xinf, Zinf)
legend('Initial profile', 'Profile after sea level rise')
dim =[.92 .5 .1 .2];
str = sprintf('A=%4.2f m^(1/3)\nSea level rise\nin 100 years
    =%4.2f m \nHs=%4.2f m \nT0=%3.1f s', A, s, Hs, T0);
annotation('textbox',dim,'String',str,'FitBoxToText','on');
```

L.3 Simplification of the cross-shore profile

```
function profile = get_simplified_profile(profile_ini, A,
    nb_iter)
%Gives a geometrical simplification from a real data profile
    n = length(profile_ini);
    %square dune, equilibrium profile starting at z=0
    zmax=max(profile_ini(:,2));
    profile = zeros(nb_iter,7,5);
    x0lagoon = -9999;
    ilagoon = 0;
    x0sea = -9999;
    isea = 0;
    for i=2:n
        if profile_ini(i,2)*profile_ini(i-1,2)<0
            if x0lagoon==-9999 %detection of the dune toe
                landward
                a = (profile_ini(i-1,2)-profile_ini(i,2))/(
                    profile_ini(i-1,1)-profile_ini(i,1));
                b = profile_ini(i,2)-a*profile_ini(i,1);
                x0lagoon = -b/a;
                ilagoon = i;
            else %detection of the dune toe seaward
                a = (profile_ini(i-1,2)-profile_ini(i,2))/(
                    profile_ini(i-1,1)-profile_ini(i,1));
                b = profile_ini(i,2)-a*profile_ini(i,1);
                x0sea = -b/a;
                isea = i;
            end
        end
    end
    if profile_ini(1,2)<x0lagoon
        a = (profile_ini(1,2))/(profile_ini(1,1)-x0lagoon);
        b = -a*x0lagoon;
    else %in case of sand bar at the begining of the profile,
        the lagoon part is considered to have a gentle slope
        a = 0.01;
        b = 0;
    end
    profile(1,:,1) = [profile_ini(1,1) profile_ini(1,2) x0lagoon
        0 a b -inf];
    a = 0;
    b = 0;
    profile(1,:,2) = [x0lagoon 0 x0lagoon zmax a b -inf];
    a = 0;
    b = zmax;
```

```
    profile(1,:,3) = [x0lagoon zmax x0sea zmax a b -inf];
    a = 0;
    b = 0;
    profile(1,:,4) = [x0sea zmax x0sea 0 a b -inf];
    profile(1,:,5) = [x0sea 0 profile_ini(n,1) -A*(profile_ini(n
        ,1)-x0sea).^(2/3) A x0sea 0];
    res = 0.01;
    X = profile_ini(ilagoon:isea,1);
    Z = profile_ini(ilagoon:isea,2);
    [X1,Z1] = plot_profile(profile(1,:,1:4), res, 1);
    vol = abs(trapz(X, Z));
    vol2 = abs(trapz(X1, Z1));
    while abs(vol-vol2)>0.01
        if vol>vol2
            zmax = zmax+zmax/2;
        else
            zmax = zmax-zmax/2;
        end
        a = 0;
        b = 0;
        profile(1,:,2) = [x0lagoon 0 x0lagoon zmax a b -inf];
        a = 0;
        b = zmax;
        profile(1,:,3) = [x0lagoon zmax x0sea zmax a b -inf];
        a = 0;
        b = 0;
        profile(1,:,4) = [x0sea zmax x0sea 0 a b -inf];
        [X1,Z1] = plot_profile(profile(1,:,1:4), res, 1);
        vol2 = abs(trapz(X1, Z1));
    end
    fprintf('The dune height is %4.2f meters.\n',zmax);
end
```

L.4 Profile discretization

```
function [X,Z] = plot_profile(profile, res, t)
    %step resolution of the plot in meters
    X=[];
    Z=[];
    [~,~,c] = size(profile);
    for j = 1:c
        if (profile(t,1,j) ~= -9999) && (profile(t,7,j) == -inf)
            nbj = abs(floor(profile(t,1,j)-profile(t,3,j))/res);
            xj = linspace(profile(t,1,j), profile(t,3,j), nbj);
            zj = profile(t,5,j)*xj + profile(t,6,j);
            X = [X xj];
            Z=[Z zj];
        elseif profile(t,1,j) ~= -9999 && profile(t,7,j) ~= -inf
            nbj = abs(floor(profile(t,1,j)-profile(t,3,j))/res);
            xj = linspace(profile(t,1,j), profile(t,3,j), nbj);
            zj = - profile(t,5,j)*(xj-profile(t,6,j)).^(2/3) +
                profile(t,7,j);
            X = [X xj];
            Z=[Z zj];
        end
    end
end
```

L.5 Profile segment discretization

```
function [X,Z] = profile_portion(profile, res, t, x1, x2)
%step resolution of the plot in meters
nb = floor(x2-x1)/res;
X=linspace(x1, x2, nb);
Z=zeros(1,nb);
[~,~,c] = size(profile);
for i=1:nb
    for j = 1:c
        if X(i) >= profile(t,1,j) && X(i) <= profile(t,3,j)
            if profile(t,7,j)==-inf
                Z(i) = profile(t,5,j)*X(i)+profile(t,6,j);
            else
                Z(i) = -profile(t,5,j)*(X(i)-profile(t,6,j)).^(2/3)+profile(t,7,j);
            end
            break
        elseif X(i) >= profile(t,3,c)
            Z(i) = -profile(t,5,c)*(X(i)-profile(t,6,c)).^(2/3)+profile(t,7,c);
        end

    end
end
```

L.6 Intersection between 2 equilibrium profiles

```
function inter = intersection(A, x01, y01, x02, y02, res, t,
    profile)
    [~,~,p] = size(profile);
    n = abs((profile(t,3,p)-max(x01, x02))/res);
    x = linspace(max(x01, x02), profile(t,3,p), n);
    y = -A*(x-x01).^(2/3)+y01 +A*(x-x02).^(2/3)-y02;
    for i = 2:n
        if y(i)*y(i-1) < 0
            a = x(i-1);
            b = x(i);
            f = -A*((a+(b-a)/2)-x01).^(2/3)+y01 +A*((a+(b-a)/2)-
                x02).^(2/3)-y02;
            bool = true;
            break
        else
            bool = false;
        end
    end
    if bool
        eps = 0.000001;
        while abs(f) > eps
            c = a + (b-a)/2;
            if ( -A*(a-x01).^(2/3)+y01 +A*(a-x02).^(2/3)-y02 ) *
                 ( -A*(c-x01).^(2/3)+y01 +A*(c-x02).^(2/3)-y02 )
               < 0
                b = c;
            else
                a = c;
            end
            f = -A*((a+(b-a)/2)-x01).^(2/3)+y01 +A*((a+(b-a)/2)-
                x02).^(2/3)-y02;
        end
        inter = [a,-A*((a+(b-a)/2)-x01).^(2/3)+y01];
    else
        inter = NaN;
    end
end
```

L.7 A parameter determination

```
function A= get_A(d50_mm, rho_s, option, velocity_method)
%Option_1 calculating settling velocity
    if option == '1'
        w = fall_velocity(d50_mm, rho_s, velocity_method);
        fprintf('The sediment fall velocity is %4.3f m/s.\n',w);
        ws_cm = w*100;
        A = 0.067*((ws_cm).^0.44);
    elseif option == '2'
%Option_2 from Moore, B.D (1982). Beach profile evolution
%in response to changes in water level and wave height.Master Thesis,
%Department of Civil Engineering, University of Delaware,Newark.
        if (d50_mm<0.4)
            A=0.41*(d50_mm.^0.94);
        elseif (d50_mm>=0.4) && (d50_mm < 10)
            A=0.23*(d50_mm.^0.32);
        elseif (d50_mm>=10) && (d50_mm<40)
            A=0.23*(d50_mm.^0.28);
        else
            A=0.46*(d50_mm.^0.11);
        end
    elseif option == '3'
%Option_3 from tabulated values of A EM 1110-2-1100 (part III) CEM.
%Cross-shore sediment transport processes.
%Tabulated values of A EM 1110-2-1100 (part III) CEM
        A_tab=
            [0.063,0.0672,0.0714,0.0756,0.0798,0.084,0.0872,0.0904,0.0936,0.

        i = ceil((d50_mm-0.1)*100);
        A  = A_tab(i);
    else
%When no option is specified, the one suggested by Kriebel & Dean is taken
%/!\ valid for d50_mm in 0.1-0.4, and water temperature of 20 degC
        w =  fall_velocity(d50_mm, rho_s, velocity_method);
        fprintf('The sediment fall velocity is %4.3f m/s.\n',w);
        A = 2.25*(w^2/9.81).^(1/3);
    end
end
```

L.8 Fall velocity calculation

```
function omega = fall_velocity(d50_mm, rho_s, method)
    d50_m = d50_mm*10^-3;
     Delta = (rho_s-1026)/1026;
     v = 1.08*10^-6; %kinematic viscosity of sea water
    if method == '1'
        %From Cheng, N. S. (1997). "A simplified settling
            velocity formula for
        %sediment particle." Journal of Hydraulic Engineering,
            123(2), 149-152.
        dx = d50_m * (Delta*9.81/(v^2)).^(1/3);
        omega = (sqrt(25+1.2*(dx^2))-5)^1.5 * (v/d50_m);
    else
        omega = (9.81*(d50_m.^2)*Delta) / (18*v);
    end
end
```

L.9 Depth of closure distance from shore

```
function [x, eq_profile] = find_x(y, profile, t)
    %Find the x coordinate in the profile at time t for a given elevation
    %eq_profile is a bolean indicating weather the searched point is in a
    %portion following an equilibrium parabola equation
    [~,~,c] = size(profile);
    x = -9999;
    for i = 1:c
        if (y > profile(t,4,i)) && (y < profile(t,2,i))
            if profile(t,7,i)==-inf
                x = (y-profile(t,6,i))/profile(t,5,i);
                eq_profile = false;
            else
                x = ((profile(t,7,i)-y)/profile(t,5,i)).^(3/2) + profile(t,6,i);
                eq_profile = true;
            end
            break
        elseif (y < profile(t,4,c))
                %disp('/!\ Point in the prolongation of the profile')
                if profile(t,7,c)==-inf
                    x = (y-profile(t,6,c))/profile(t,5,c);
                    eq_profile = false;
                else
                    x = ((profile(t,7,c)-y)/profile(t,5,c)).^(3/2) + profile(t,6,c);
                    eq_profile = true;
                end
                break
        end
    end
    if x == -9999
        disp('/!\ Point not found')
    end
end
```

L.10 Wave propagation

```
function [H] = propagation (H0, T0, d, alpha0)
    d = abs(d);
    alpha0 = deg2rad(alpha0);
    L0 = (9.81*(T0^2))/(2*pi);
    L1 = L0*tanh((2*pi*d)/L0);
    a = 0.001; %threshold
    while abs(L0-L1)>= a
        L0 = L1;
        L1 =  (9.81*(T0^2))/(2*pi)* tanh((2*pi*d)/L0);
    end
    L = L0; %wavelength
    alpha = asin(sin(alpha0)*L/L0);
    K = (2*pi) / L; %wavenumber
    Kr = sqrt(cos(alpha0)/cos(alpha)); %reflection coef
    Ksh = 1 / sqrt( (1 + (2*K*d)/sinh(2*K*d)) * tanh(K*d)); %
        shoaling coef
    H  = H0 * Kr * Ksh;
end
```

L.11 Wave breaking

```
function [Hb, db] = breaking(H0, T0, alpha0, gamma, profile, t)
    [~,~,a] = size(profile);
    d0 = profile(t,5,a);
    d = abs(d0);
    [H] = propagation (H0, T0, d, alpha0);
%   gamma = 0.78; %breaking index Mc Cowan theory
%   %gamma = 0.5 - 0.65; %breaking index Batnes theory
%   Hb = gamma * d; %wave breaking criteria
    while abs(H/d-gamma) >0.000001
        if H/d > gamma
            d = d + d/2;
            [H] = propagation (H0, T0, d, alpha0);
        else
            d = d - d/2;
            [H] = propagation (H0, T0, d, alpha0);
        end
    end
    Hb = H;
    db=[-9999, -(Hb/gamma)];
    [xb, eq_profile] = find_x(db(2), profile, t);
    if eq_profile
        db(1) = xb;
    else
        db(1) = xb;
        disp('/!\ Breaking depth not in the equilibium profile
            part')
    end
end
```

L.12 Run up calculation

```
function [R, beta] = run_up(H0, T0, alpha0, gamma, profile, t, beta_option, runup_option, S)
    [Hb, db] = breaking(H0, T0, alpha0, gamma, profile, t);
    if beta_option == '1' %average slope from breaking point to mean swash location (foreshore beach slope)
        x0 = profile(t,3,4);
        y0 = profile(t,4,4);
        beta = abs((y0-db(2)) / (x0-db(1)));
    else %Graph from Wiegel, R.L., 1965. Oceanographical Engineering, Prentice-Hall, 531 pages
        beta = 1/15;
    end
    if runup_option == '1' %Method from Stockdon et al 2006, " Empirical
    %parameterization of setup, swash, and runup"
        L0 = (9.81*(T0^2))/(2*pi);
        xhi_0 = beta/(H0/L0);
        if xhi_0 <0.3
            R = 0.043*sqrt(H0*L0);
        else
            R = 1.1*( 0.35*beta*sqrt(H0*L0) + 0.5*sqrt(H0*L0*(0.563*beta^2+0.004)) );
        end
    elseif runup_option == '2'
        %Method from Hughes 2004, "Estimation of wave run-up on smooth, impermeable slopes using the wave momentum flux parameter"
        if abs(beta)>=1/30 && abs(beta)<=1/5
            d = abs(db(2));
            A0 = 0.6392*( (Hb/(S+d))^2.0256 );
            A1 = 0.1804*( (Hb/(S+d))^(-0.391) );
            Mmax = A0* ( (S+d)/(9.81*T0^2) )^(-A1);
            R = 4.4 * (S+d) * abs(beta)^0.7 * sqrt(Mmax);
        else
            disp('Change method for run up, slope not in the range')
            return
        end
    end
    fprintf('The steepness of the beach is %4.2f rad, the run up 2%% is %4.2f m.\n',beta, R);
end
```

L.13 Retreat calculation with convolution method

```
function [R_Td, R_inf] = convolution(Ts, Td, S, db, profile , t)
%Ts : characteristic time scale , set as 60 hours from grpah p
    .221 in
%Kriebel & Dean 93
%Td : storm duration , typically 24 hours in the Ebro delta area
%db : breacking depth called hb in Kriebel & Dean 93
    %Maximum potential retreat
    db(2) = abs(db(2));
    m = 0;
    B = profile(t,2,3);
    D = 0;
    R_inf = ( S*db(1) ) / (B+db(2)-S/2);
    %Retreat due to the storm
    beta = 2*pi*Ts/Td;
    R_Td = (R_inf/2)*( 1-(beta^2/(1+beta^2))*exp(-Td/Ts) - 1/(1+
        beta^2) );

end
```

L.14 Erosion function

```
function [D_retreat, D_height, D_width, profile_int, profile_int2,breach] = erosion2(Ts, Td, S, db, profile, t, res)
  breach = false;
  [R, ~] = convolution(Ts, Td, S, db, profile, t);
  profile_int = zeros(1,7,7);
  profile_int(1,:,1:5) = profile(t,:,:);
 A = profile(t,5,5);
  a = -S/R;
  found = false;
  if profile(t,3,3)-R > profile(t,1,3)
      profile_int(1,3,3) = profile(t,3,3)-R; %the seaward part of the dune is reduced of R
      profile_int(1,1:4,4) = [profile(t,1,4)-R profile(t,2,4) profile(t,3,4)-R profile(t,4,4)+S];
      y = -A*(profile(t,3,5)-(profile(t,6,5)-R))^(2/3) + profile(t,7,5)+S;
      profile_int(1,:,5) = [profile(t,1,5)-R profile(t,2,5)+S profile(t,3,5) y A profile(t,6,5)-R profile(t,7,5)+S];
      profile_int2 = profile_int(1,:,1:5);
      if -A*(profile(t,6,5)-(profile(t,6,5)-R))^(2/3) + profile(t,7,5)+S > profile(t,7,5)
      %case where the new profiles intersects the ancient one not in the
      %equilibrium profile part but in the dune edge seaward
          x = linspace(profile(t,1,5)-R, db(1), 1000);
          x = x(2:length(x));
          [X1,Z1] = profile_portion(profile, res, t, profile(t,6,5)-R, db(1));
          vol1 = trapz(X1, Z1-db(2));
          for xb = x
              yb = -A*(xb-(profile(t,6,5)-R))^(2/3) + profile(t,7,5)+S;
              profile_int(1,3:4,5) = [xb yb];
              profile_int(1,:,6) = [xb yb xb+R yb-S a yb-a*xb -inf];
              profile_int(1,:,7) = [xb+R yb-S profile(t,3,5) profile(t,4,5) A profile(t,6,5) profile(t,7,5)];
              [~,Z2] = profile_portion(profile_int, res, 1, profile(t,6,5)-R, db(1));
              vol2 = trapz(X1, Z2-db(2));
              volsmall = vol1-vol2;
```

```
                if volsmall <= 0
                    found = true;
                    break
                end
            end
            if found == false
                disp('In erosion, no intersection, too small volumes')
                profile_int = profile(t,:,:);
                profile_int2 = profile_int;
            end
        else
            tic
            inter = intersection(A, profile(t,6,5), profile(t,7,5),profile(t,6,5)-R, profile(t,7,5)+S, res, t, profile);
            x = linspace(inter(1),profile(t,3,5), 1000);
            x = x(2:length(x));
            for xb = x
                yb = -A*(xb-(profile(t,6,5)-R))^(2/3) + profile(t,7,5)+S;
                profile_int(1,3:4,5) = [xb yb];
                profile_int(1,:,6) = [xb yb xb+R yb-S a yb-a*xb -inf];
                profile_int(1,:,7) = [xb+R yb-S profile(t,3,5) profile(t,4,5) A profile(t,6,5) profile(t,7,5)];
                [X1,Z1] = profile_portion(profile, res, t, profile(t,6,5)-R, xb+R);
                [~,Z2] = profile_portion(profile_int, res, 1, profile(t,6,5)-R, xb+R);
                vol1 = trapz(X1, Z1-(yb-S));
                vol2 = trapz(X1, Z2-(yb-S));
                vol = vol1-vol2;
                if vol <= 0
                    found = true;
                    break
                end
            end
            if found == false
                disp('In erosion, intersection too ofshore to be in the profile')
                profile_int = profile_int2;
                toc
            end
        end
```

```
    else
        disp('/!\ Dune entirely eroded, BREACH\n')
        breach = true;
        profile_int = profile_int(1,:,1:5);
        profile_int(1,:,2) = [profile(t,3,1) profile(t,4,1) profile(t,3,1) profile(t,4,1) 0 profile(t,4,1) -inf];
        profile_int(1,1:6,3) = [profile(t,3,1) profile(t,4,1) profile(t,1,5) profile(t,4,1) 0 profile(t,4,1)];
        profile_int(1,:,4) = [profile(t,1,5) profile(t,4,1) profile(t,1,5) profile(t,4,1) 0 profile(t,4,1) -inf];
        profile_int2 = profile_int;
    end
    D_retreat = profile(1,1,5)-profile_int(1,1,5);
    D_height = profile_int(1,4,3)-profile_int(1,2,5);
    D_width = profile_int(1,3,3)-profile_int(1,1,3);
end
```

L.15 Embankment structure

```
function [A, X, Z] = embankment(phi, slope, Q)
    beta = atan(abs(slope));
    alpha1 = pi/2-beta;
    alpha2 = pi/2-phi;
    omega = pi/2-(beta+phi);
    H = sqrt((2*Q) / (sin(alpha1)/sin(beta)+sin(alpha2)/sin(phi)
        ));
    A = H/sin(beta);
    C = H/sin(phi);
    X = C*sin(omega);
    Z = C*cos(omega);
end
```

L.16 Overwashed volumes calculation

```
function [qsw, qd, type] = overwash_volumes(profile, Ru, S, db, beta, t)
    B = profile(t,3,2);
    if S> profile(t,4,3)
        Kr = 0.0007; %calibration coefficient, 0.005 is the recommendation
        %from Donnelly et al (2009)
        Zr = S+Ru-B ; %run up elevation relative to dune
        %crest elevation
        qdr = 2 * Kr * sqrt(2*9.81) * Zr^(3/2) * sqrt(1-B/Ru);
        Ki = 0.0001; %calibration coefficient, 0.005 is the recommendation
        %from Donnelly et al (2009)
        qd = 2 * Ki * sqrt(2*9.81) * Zr^(3/2) + qdr;
        type = 'Inundation';
        %fprintf('Inundation overwash, qd is %6.4f m^3, ',qd);
    else
        Kr = 0.0001; %calibration coefficient, 0.005 is the recommendation
        %from Donnelly et al (2009)
        Zr = S+Ru-B ; %run up elevation relative to dune
        %crest elevation
        qd = 2 * Kr * sqrt(2*9.81) * Zr^(3/2) * sqrt(1-B/Ru);
        type = 'Run up     ';
        %fprintf('Run up overwash, qd is %6.4f m^3, ',qd);
    end
    Ksw = 0.001; %calibration coefficient, 0.0016 is the recommendation
    %from Donnelly et al (2009)
    beta_eq = profile(1,5,5)*( (profile(t,3,4).^(2/3)-db(1).^(2/3))/(profile(t,3,4)-db(1)) );
    qsw = 2 * Ksw * sqrt(2*9.81) * Ru^(3/2) * (beta - beta_eq);
%      fprintf('and, qsw is %6.4f m^3.\n',qsw);
end
```

L.17 Overwash function

```
function [D_retreat, D_height, D_width, profile_int, profile_int2, breach] = overwash (qsw, qd, profile, phi, S, t, res)
%Reduce the dune height and of qd m^3 and place this volume at the toe of
%the dune as a scarp. Erode the dune of qsw m^3 and redraw an equilibrium
%profile.
%qsw : over-washed volume seaward in m^3
%qd : over-washed volume landward in m^3
%profile : matrix containing the modelled profile at each time step until
%t-1
%t : time step
%phi : friction angle of the sand in radians
    breach = false;
    A = profile(t,5,5);
    profile_int = zeros(1,7,7);
    profile_int(1,:,1:5) = profile(t,:,:);

%SEAWARD TRANSPORT--------------------------------------------------------
    %Initialization
    y02 = profile(t,2,5)+S;
    threshold_x02 = profile(t,6,5)-((y02-profile(t,7,5))/A).^(3/2); %if x02 is greater than this value, there is no intersection
    vol_dune_ini = (profile_int(1,4,3)-profile_int(1,2,5))*(profile_int(1,3,3)-profile_int(1,1,3))
    if threshold_x02 > profile(t,1,3) && threshold_x02 < profile(t,3,3)
        x = linspace(profile(t,1,3), threshold_x02, 1000);
        x = x(2:length(x)-1);
        x = fliplr(x);
        found = false;
        for x02 = x
            inter = intersection(A, profile(t,6,5), profile(t,7,5), x02, y02, res, t, profile);
            profile_int(1,:,5) = [x02 y02 profile(t,3,5) profile(t,4,5) A x02 y02];
            profile_int(1,1:4,4) = [x02 profile(t,4,3) x02 y02];
            profile_int(1,3,3) = x02;
            [X1,Z1] = profile_portion(profile, res, t, x02,
```

```
            inter(1));
            [~,Z2] = profile_portion(profile_int, res, 1, x02, inter(1));
            vol1 = trapz(X1, Z1-inter(2));
            vol2 = trapz(X1, Z2-inter(2));
            vol = vol1-vol2;
            if vol-qsw >= 0
                found = true;
                break
            end
        end
        if found == false
            fprintf('In overwash, seaward transport, problem of x resolution\n');
        end
    else
        fprintf('Dune entirely eroded, BREACH 111\n');
        breach = true;
        profile_int = profile_int(1,:,1:5);
        profile_int(1,:,2) = [profile(t,3,1) profile(t,4,1) profile(t,3,1) profile(t,4,1) 0 profile(t,4,1) -inf];
        profile_int(1,1:6,3) = [profile(t,3,1) profile(t,4,1) profile(t,1,5) profile(t,4,1) 0 profile(t,4,1)];
        profile_int(1,:,4) = [profile(t,1,5) profile(t,4,1) profile(t,1,5) profile(t,4,1) 0 profile(t,4,1) -inf];
        profile_int2 = profile_int;
        return
    end
    fprintf('The equilibrium origin has been risen by %6.4f m, and the dune has been eroded by %6.4f m\n',y02-profile(t,2,5), profile(t,3,3)-x02);
    profile_int2 = profile_int;
    profile_int2(1,2,5) = profile(t,2,5);
    profile_int2(1,7,5) = profile(t,7,5);
    %Mass balance of the volume taken from the dune, offshore deposition
    stop = [inter(1)+10 -A*(inter(1)+10-x02).^(2/3)+y02];
    a = -tan(phi);
    b = stop(2)-a*stop(1);
    profile_int(1,3:4,5) = stop;
    toe = stop(1)+(stop(2)-(-A*(stop(1)-profile(t,6,5)).^(2/3)+profile(t,7,5)))/tan(phi);
    profile_int(1,:,6) = [stop(1) stop(2) toe a*toe+b a b -inf];
    profile_int(1,:,7) = [toe a*toe+b profile(t,3,5) profile(t,4,5) ...
        profile(t,5,5) profile(t,6,5) profile(t,7,5)];
```

```
    [X1,Z1] = profile_portion(profile, res, t, inter(1), stop(1)
        );
    [~,Z2] = profile_portion(profile_int, res, 1, inter(1), stop
        (1));
    vol1 = trapz(X1, Z1-(-A*(stop(1)-profile(t,6,5)).^(2/3)+
        profile(t,7,5)));
    vol2 = trapz(X1, Z2-(-A*(stop(1)-profile(t,6,5)).^(2/3)+
        profile(t,7,5)));
    vol = vol2-vol1;
    eps = 0.01*(profile(t,4,3)-profile(t,2,5))*(profile(t,3,3)-
        profile(t,1,3)); %tolerated error of 1% of the dune
        volume;
    while abs(vol-qsw)>eps
        if vol>qsw
            stop(1) = stop(1) - stop(1)/50;
            div = 50;
            while stop(1)<= inter(1)
                stop(1) = stop(1)/(1+1/div);
                div = div/2;
                stop(1) = stop(1) - stop(1)/div;
            end
        else
            stop(1) = stop(1) + stop(1)/50;
        end
        stop(2) = -A*(stop(1)-x02).^(2/3)+y02;
        b = stop(2)-a*stop(1);
        profile_int(1,3:4,5) = stop;
        toe = stop(1)+(stop(2)-(-A*(stop(1)-profile(t,6,5))
            .^(2/3)+profile(t,7,5)))/tan(phi);
        if toe > profile(t,3,5)
            stop(1) = profile(t,3,5);
            stop(2) = -A*(stop(1)-x02).^(2/3)+y02;
            profile_int(1,3:4,5) = stop;
            profile_int = profile_int(1,:,1:5);
            out = true;
        else
            out = false;
            profile_int(1,:,6) = [stop(1) stop(2) toe a*toe+b a
                b -inf];
            profile_int(1,:,7) = [toe a*toe+b profile(t,3,5)
                profile(t,4,5) ...
                 profile(t,5,5) profile(t,6,5) profile(t,7,5)];
            [X1,Z1] = profile_portion(profile, res, t, inter(1),
                stop(1));
            [~,Z2] = profile_portion(profile_int, res, 1, inter
                (1), stop(1));
```

```
            vol1 = trapz(X1, Z1-stop(2));
            vol2 = trapz(X1, Z2-stop(2));
            vol = vol2-vol1;
        end
        if out
            break
        end
    end

    %LANDWARD TRANSPORT--------------------------------------------------

    vol_dune = (profile_int(1,4,3)-profile_int(1,2,5))*(profile_int(1,3,3)-profile_int(1,1,3)) %remaining volume after seaward erosion
    if vol_dune > qd
        z = qd/(profile_int(1,3,3)-profile_int(1,1,3));
        fprintf('and reduced by %6.4f m.\n',z);
        [H, I, J] = embankment(phi, profile(t,5,1), qd);
        if profile(t,4,3)-z >= profile_int(1,2,5)
            x_top_seaward = x02;
            profile_int(1,1:4,4) = [x_top_seaward profile(t,2,4)-z profile_int(1,1,5) profile_int(1,2,5)];
            profile_int(1,4,2) = profile(t,4,2)-z;
            profile_int(1,:,3) = [profile(t,1,3) profile(t,2,3)-z ...
            x_top_seaward profile(t,4,3)-z 0 profile(t,2,3)-z -inf];

            profile_int2(1,:,2:4) = profile_int(1,:,2:4);
           w = qd/(profile_int(1,2,3)-profile_int(1,4,1));
            profile_int2(1,1,3) = profile_int(1,1,3)-w;
            profile_int2(1,1,2) = profile_int(1,1,3)-w;
            profile_int2(1,3,2) = profile_int(1,1,3)-w;
            if profile(t,1,1) < profile_int2(1,1,3)
                a = profile(t,5,1);
                b = profile_int2(1,2,2) - a * profile_int2(1,1,2);
                profile_int2(1,:,1) = [profile(t,1,1) a*profile(t,1,1)+b profile_int2(1,1,2) profile_int2(1,2,2) a b -inf];
            else
                profile_int2(1,1:6,1) = [profile_int2(1,1,1)-(profile_int2(1,3,1)-profile_int2(1,1,2)) profile_int2(1,2,1)-(profile_int2(1,4,1)-profile_int2(1,2,2))...
```

```
                    profile_int2(1,3,1)-(profile_int2(1,3,1)-profile_int2(1,1,2)) profile_int2(1,4,1)-(profile_int2(1,4,1)-profile_int2(1,2,2)) ...
                    a b-(profile_int2(1,3,1)-profile_int2(1,1,2))];
            end
        else
            x_top_seaward = ((profile_int(1,7,5)-(profile(t,2,3)-z))/A).^(3/2) + profile_int(1,6,5);
            profile_int(1,1:2,5) = [x_top_seaward, profile(t,2,3)-z];
            profile_int(1,1:4,4) = [profile_int(1,1,5) profile_int(1,4,3) profile_int(1,1,5) profile_int(1,2,5)];
            profile_int(1,:,3) = [profile(t,1,3) profile(t,2,3)-z ...
            profile_int(1,1,5) profile(t,4,3)-z 0 profile(t,2,3)-z -inf];
            profile_int2 = profile_int;
        end

        if (profile(t,3,1)-profile(t,1,1)) > H+I
            %case where the toe is fitting in the profile
            profile_int = cat(3,zeros(1,7,2),profile_int);
            profile_int(1,:,1) = [profile(t,1,1) profile(t,2,1) ...
                profile(t,3,1)-(H+I) profile(t,4,1)-J profile(t,5,1)  profile(t,6,1) -inf];
            profile_int(1,:,2) = [profile(t,3,1)-(H+I) profile(t,4,1)-J ...
                profile(t,3,1)-(H)  profile(t,2,2) ...
                tan(phi) profile(t,2,2)-tan(phi)*(profile(t,3,1)-(H)) -inf];
            profile_int(1,:,3) = [profile_int(1,3,2) profile(t,2,2) ...
                profile(t,1,2) profile(t,2,2) 0 profile(t,2,2) -inf];

            D_retreat = profile(1,1,5)-profile_int(1,1,7);
            D_height = profile_int(1,4,5)-profile_int(1,2,7);
            D_width = profile_int(1,1,5)-profile_int(1,3,5);
        elseif profile(t,3,1)-profile(t,1,1) <= H
            %case where the toe is too big to fit in the profile
            profile_int(1,:,1) = [profile(t,1,1) profile(t,2,2) ...
```

```
                    profile(t,3,1) profile(t,2,2) 0 profile(t,2,2) -inf];
                D_retreat = profile(1,1,5)-profile_int(1,1,5);
                D_height = profile_int(1,4,3)-profile_int(1,2,5);
                D_width = profile_int(1,3,3)-profile_int(1,1,3);
            else
                %case where the toe is partially fitting in the profile
                profile_int = cat(3,zeros(1,7,1),profile_int);
                slpe = profile(t,4,1) - tan(phi)*(profile(t,3,1)-H);
                profile_int(1,:,1) = [profile(t,1,1) tan(phi)*profile(t,1,1)+slpe ...
                    profile(t,3,1)-(H) profile(t,4,1) tan(phi) slpe -inf];
                profile_int(1,:,2) = [profile(t,3,1)-(H) profile(t,4,1) ...
                    profile(t,1,2) profile(t,2,2) 0 profile(t,2,2) -inf];

                D_retreat = profile(1,1,5)-profile_int(1,1,6);
                D_height = profile_int(1,4,4)-profile_int(1,2,6);
                D_width = profile_int(1,3,4)-profile_int(1,1,4);
            end
            vol_dune_lagoon = (profile_int(1,4,3)-profile_int(1,2,5))*(profile_int(1,3,3)-profile_int(1,1,3))
        else
            fprintf('Dune entirely eroded, BREACH 222\n');
            breach = true;
            profile_int = profile(t,:,:);
            profile_int(1,:,2) = [profile(t,3,1) profile(t,4,1) profile(t,3,1) profile(t,4,1) 0 profile(t,4,1) -inf];
            profile_int(1,1:6,3) = [profile(t,3,1) profile(t,4,1) ...
                profile(t,1,5) profile(t,4,1) 0 profile(t,4,1)];
            profile_int(1,:,4) = [profile(t,1,5) profile(t,4,1) profile(t,1,5) profile(t,4,1) 0 profile(t,4,1) -inf];
            profile_int2 = profile_int;
            D_retreat = profile(1,1,5)-profile_int(1,1,5);
            D_height = profile_int(1,4,3)-profile_int(1,2,5);
            D_width = profile_int(1,3,3)-profile_int(1,1,3);
            return
        end

end
```

L.18 Settlement function

```
function [time, U, Z, Zc, timeyr, rate, Tv] = settlment(Cv,h, Zc
    )
%primary consolidation
%h in meters
%Cv in cm2/s
%       Zc = h*(e0-e)/(1+e0);
    U = 1:0.1:99.9;
    n = length(U);
    Tv = zeros(1,n);
    Z = zeros(1,n);
    time = zeros(1,n);
    i=0;
    for u = U
        i = i+1;
        Z(i) = (u/100)*Zc;
        if (u/100)<= 0.526
            Tv(i) =(pi/4)*(u/100)^2;
        else
            Tv(i) =1.781-0.933*log(100-u);
        end
        time(i) = (h*100)^2*(Tv(i)/Cv);
    end
    timeyr = time(1):31536000:time(n);
    i=0;
    Zt = zeros(1,length(timeyr));
    rate = zeros(1,n);
    for yr = timeyr
        i=i+1;
        Tvt = yr*Cv/(h*100)^2;
        ut = sqrt((4*Tvt)/pi);
        if ut>=0.526
            ut = 1-exp((0.085+Tvt)/(-0.933));
        end
        Zt(i) = Zc*ut;
        if i>=2
            rate(i) = Zt(i)-Zt(i-1);
        end
    end
    time = time/(3600*24*365);

    timeyr = timeyr/(3600*24*365);
    rate(133) = rate(132);
    rate(1) = 0.335;
end
```

L.19 Sea level rise impact using Bruun rule

```
function [R_bruun, profile_int, lvl] = slr(x_doc, z_doc, date, profile, t)
    profile_int = profile(t,:,:);
    lvl = 3.355e-05*date.^2 -0.1312*date + 128.2;
    R_bruun = lvl * (x_doc-profile(t,1,3))/((profile(t,4,3)-profile(t,2,5))+abs(z_doc));
    if t>1
        lvl = lvl - (profile(t,2,5)-profile(1,2,5));
        R_bruun = R_bruun - (profile(1,1,5)-profile(t,1,5));
    end
    profile_int(1,:,1) = [profile(t,1,1)-R_bruun, profile(t,2,1)+lvl, profile(t,3,1)-R_bruun, profile(t,4,1)+lvl, profile(t,5,1), profile(t,2,1)+lvl-profile(t,5,1)*(profile(t,1,1)-R_bruun), -inf];
    profile_int(1,:,2) = [profile(t,1,2)-R_bruun, profile(t,2,2)+lvl, profile(t,3,2)-R_bruun, profile(t,4,2)+lvl, 0, profile(t,4,2)+lvl, -inf];
    profile_int(1,:,3) = [profile(t,1,3)-R_bruun, profile(t,2,3)+lvl, profile(t,3,3)-R_bruun, profile(t,4,3)+lvl, 0, profile(t,4,2)+lvl, -inf];
    profile_int(1,:,4) = [profile(t,1,4)-R_bruun, profile(t,2,4)+lvl, profile(t,3,4)-R_bruun, profile(t,4,4)+lvl, 0, profile(t,4,2)+lvl, -inf];
    profile_int(1,:,5) = [profile(t,1,5)-R_bruun, profile(t,2,5)+lvl, profile(t,3,5)-R_bruun, profile(t,4,5)+lvl, profile(t,5,5), profile(t,6,5)-R_bruun, profile(t,7,5)+lvl];
    %D_retreat = profile(t,1,5)-profile_int(1,1,5);
end
```

L.20 Storms random generation

```
function storms_yr = storm_generation(A, B, C, D, E, lambda, pd,
    yr, Td)
% 3.02,0.59,0.97, 3.74, 0.55 lambda 6.53
% pd = [0 0.07 0.1 0.14 0.17 0.2 0.23 0.29 0.33 0.36 0.6 ;0.5
    0.8 0.9 0.95 0.98 0.99 0.995 0.998 0.999 0.9995 1];
%storms_yr = [yr, day, Hs, Tp, alpha, s, Td]
    %initialization
    lambda_year = round(normrnd(lambda,0.7)); %numbers of storms
        in the year
    storms_yr_s = zeros(lambda_year, 6);

    %repartition of the storms in the year
    calendar = 1:1:365;
    storms = zeros(1,lambda_year);
    for i = 1:lambda_year
        n = length(calendar);
        date_index = randsample(1:1:n,1); %date assignment for
            each storm
        date = calendar(date_index);
        dp = 6;
        while date_index+dp > length(calendar)
            if dp == 0
                break
            else
                dp = dp-1;
            end
        end
        while calendar(date_index+dp) ~= date+dp
            if dp == 0
%                   disp('break1')
                break
            else
                dp = dp-1;
            end
        end
        dn = 6;
        while date_index-dn < 1
            if dn == 0
                break
            else
                dn = dn-1;
            end
        end
        while calendar(date_index-dn) ~= date-dn
```

```
            if dn == 0
%                disp('break2')
                break
            else
                dn = dn-1;
            end
        end
        calendar = [calendar(1:date_index-dn), calendar(date_index+dp:n)];
        storms(i) = date;
    end
    storms = sort(storms);
    storms_yr_s(:,1) = storms;
    %generations of the conditions for each storm
    for i = 1:lambda_year
        x = rand();
        storms_yr_s(i,2) = B*(-log(1-x))^(1/C)+A; %storm wave height
        storms_yr_s(i,3) = D * storms_yr_s(i,2)^E; %storm period
        storms_yr_s(i,4) = deg2rad(randsample([0 45 90 135 180 225 270 315],1, true, [0.03 0.05 0.25 0.16 0.24 0.09 0.08 0.1])); %storm direction
        %storm surge
        x = rand();
        for j=1:(length(pd)-1)
            if pd(2,j) <= x && x <= pd(2,j+1)
                storms_yr_s(i,5) = (pd(1,j+1)-pd(1,j)) * (x-pd(2,j))/(pd(1,j+1)-pd(1,j)) + pd(1,j);
            end
        end
        %Td = normrnd(24*0.84,2.5)*3600; %storm duration
        storms_yr_s(i,6) = Td;
    end
    storms_yr = [];
    for i = 1:lambda_year
        if storms_yr_s(i,5) ~= 0
            storms_yr = [storms_yr; [yr storms_yr_s(i,:)]];
        end
    end
end
```